Unveiling the link between

Supermassive Black Holes and Galaxies

Cosmology talk @ Berkeley Sept. 1 2015

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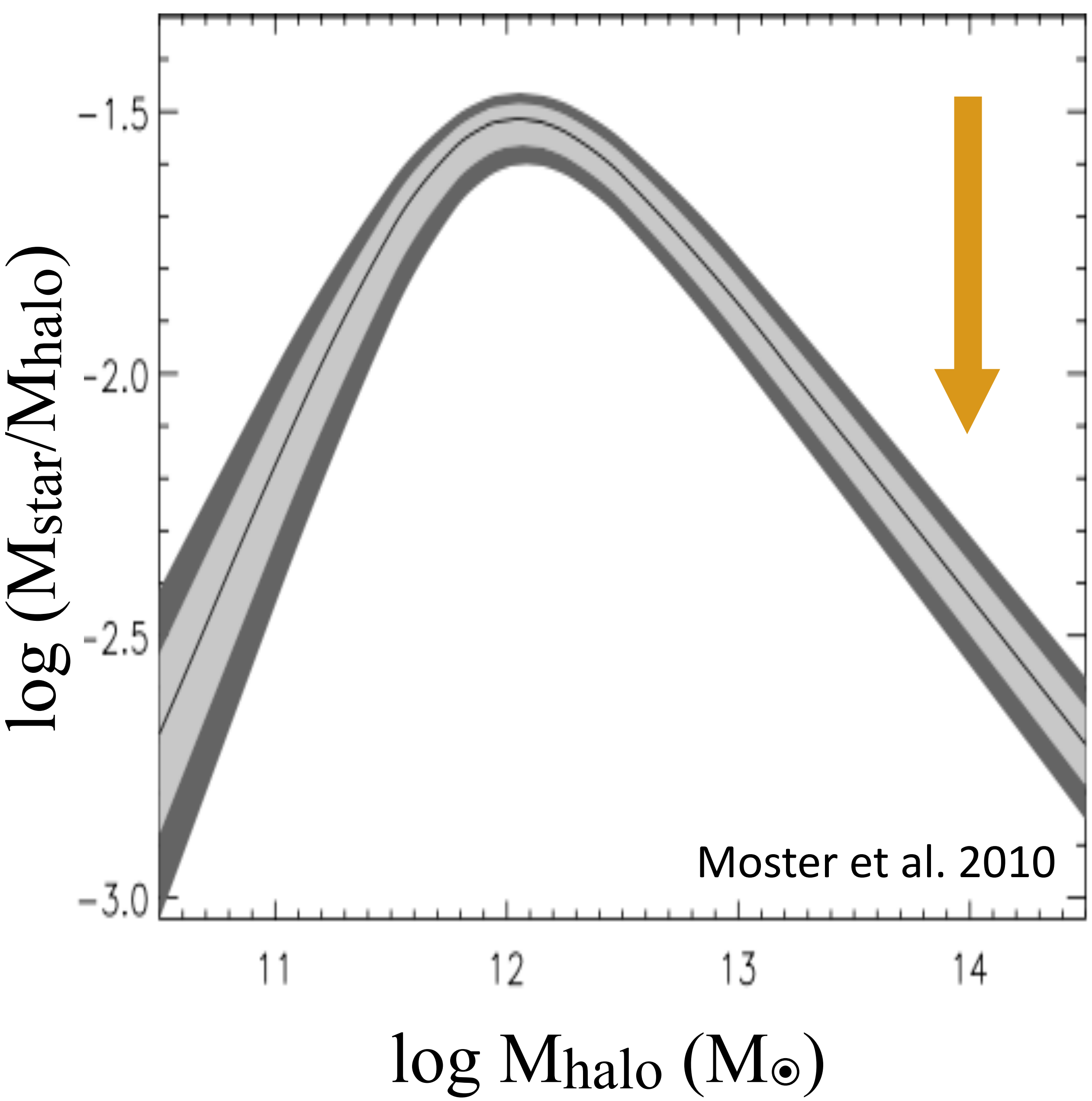
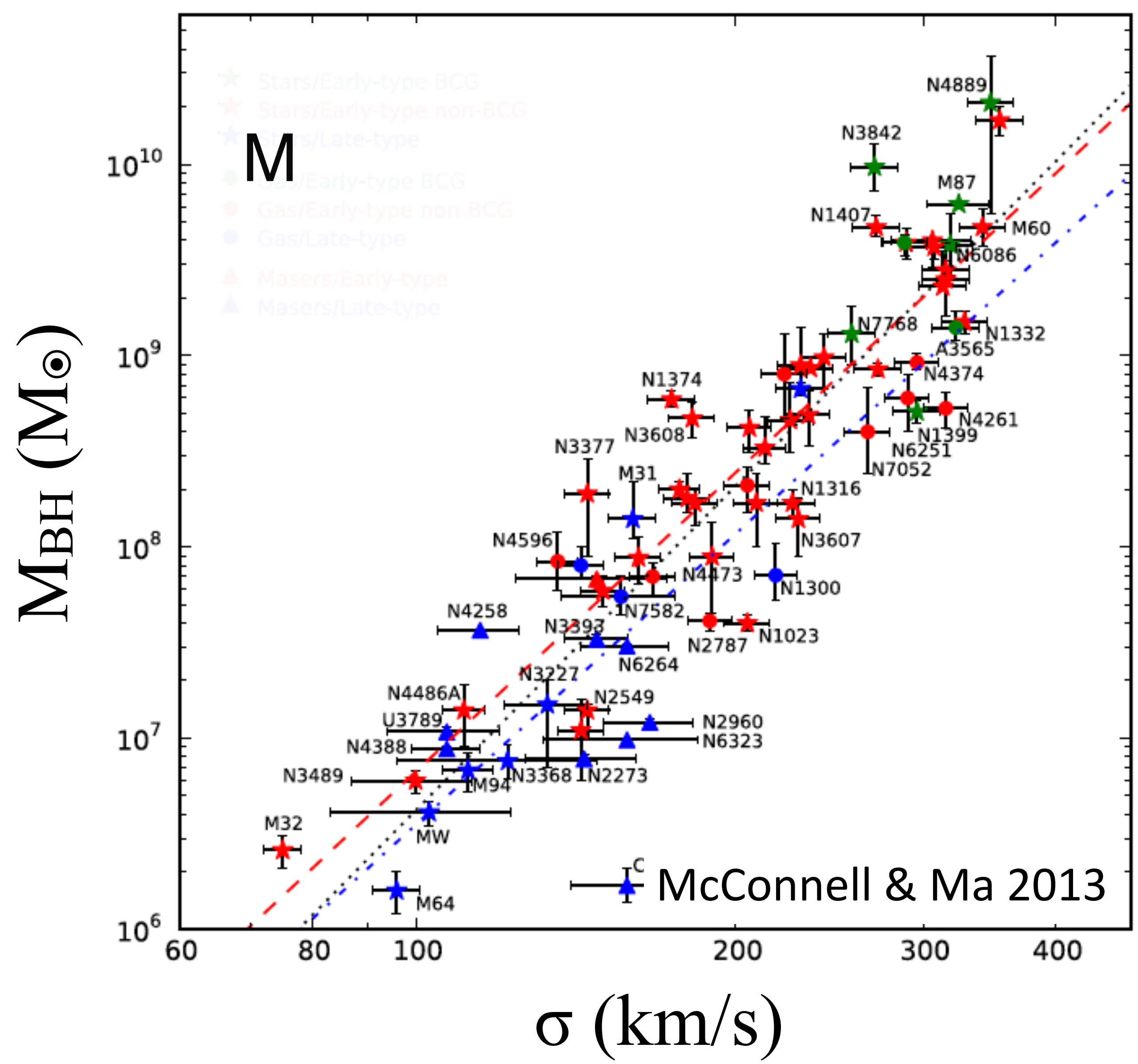
Princeton University, Advisor: Jenny Greene

Puzzles in Galaxy Evolutions

Suppressed Star Formation



Black Hole Masses Correlate with Host Galaxies



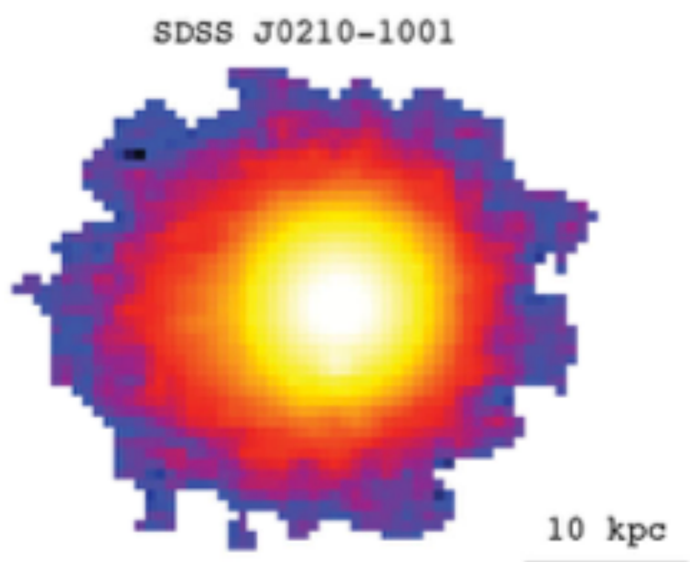
Active Galactic Nuclei (AGN) Feedback

Silk & Rees 1998
Matteo et al. 2005
DeBuhr et al. 2011

Luminous AGN drive outflows

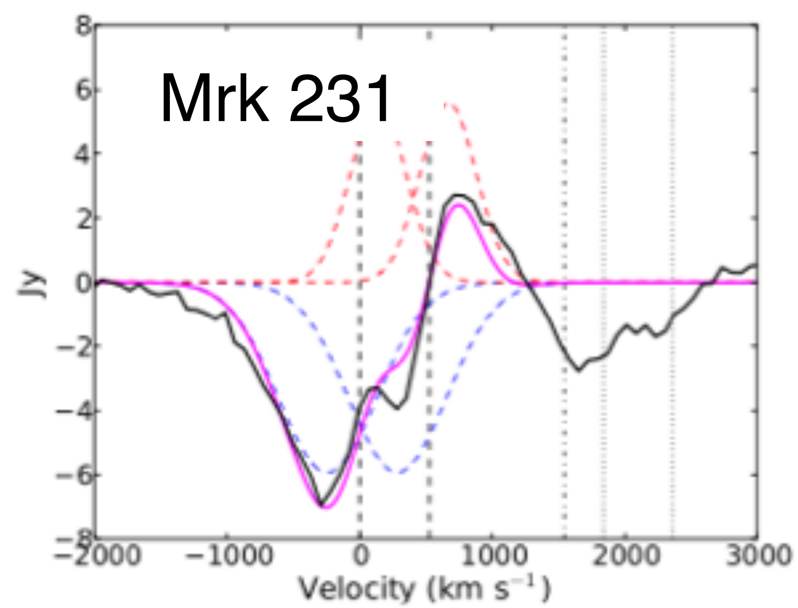
Ionized outflows ~ 10 kpc

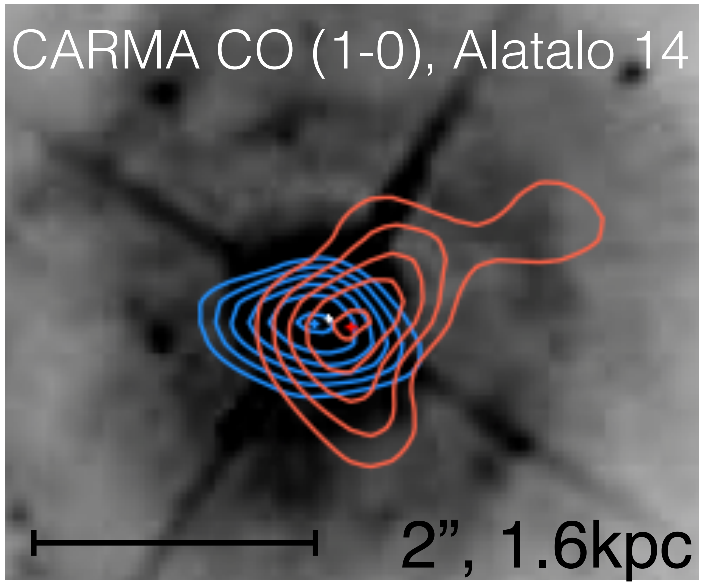
Gemini IFU, Liu+13



Molecular outflows < 1 kpc

Herschel OH 119 µm spectroscopy. Veilleux+13





Outline:

Part I: Multi-phase feedback prototype

Molecular Outflows in J1356 with ALMA

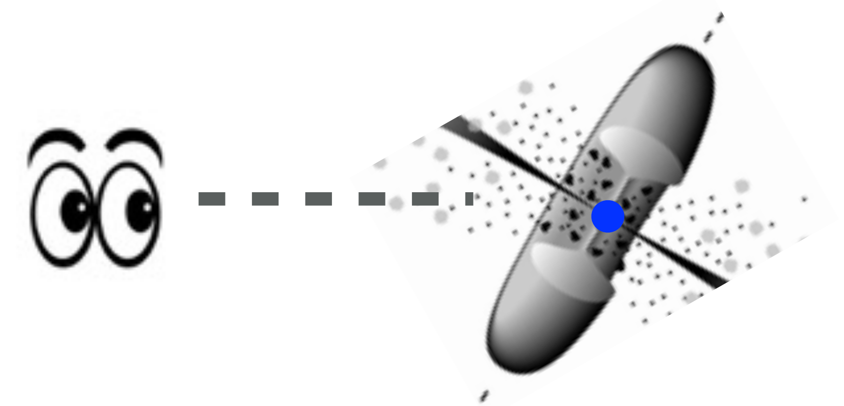
Part II: Is outflow common?

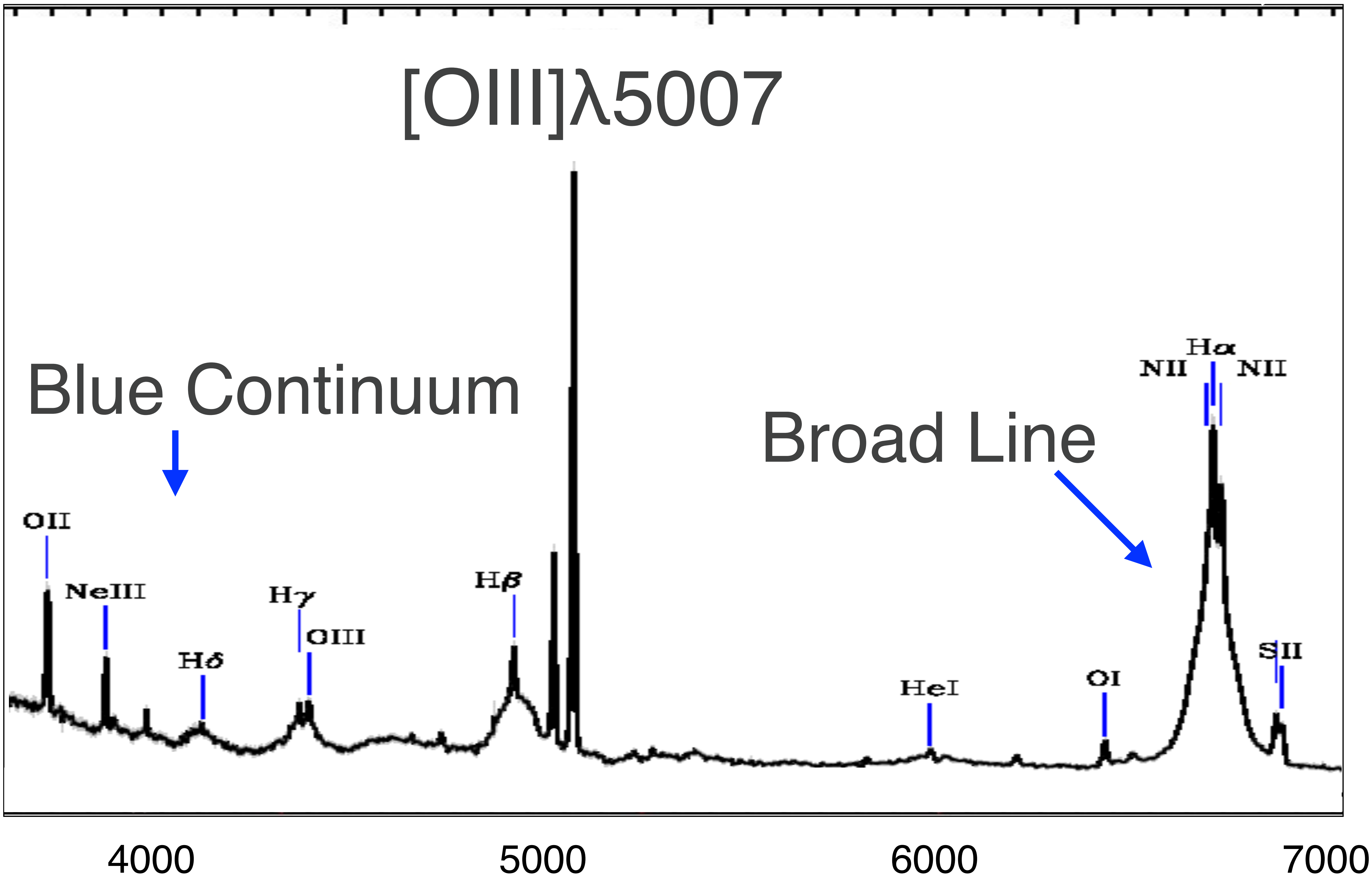
Ionized Outflows in Luminous Obscured Quasars

Part III: Explore a new population

Imaging Selection of Extended Outflows

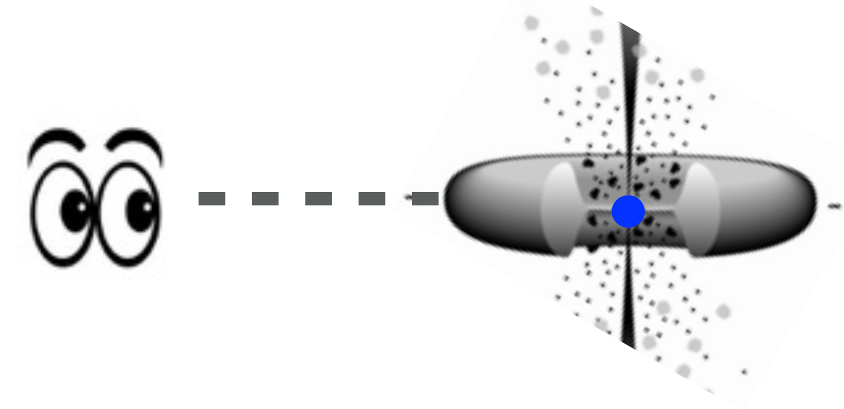
Unobscured (Type-1) AGN

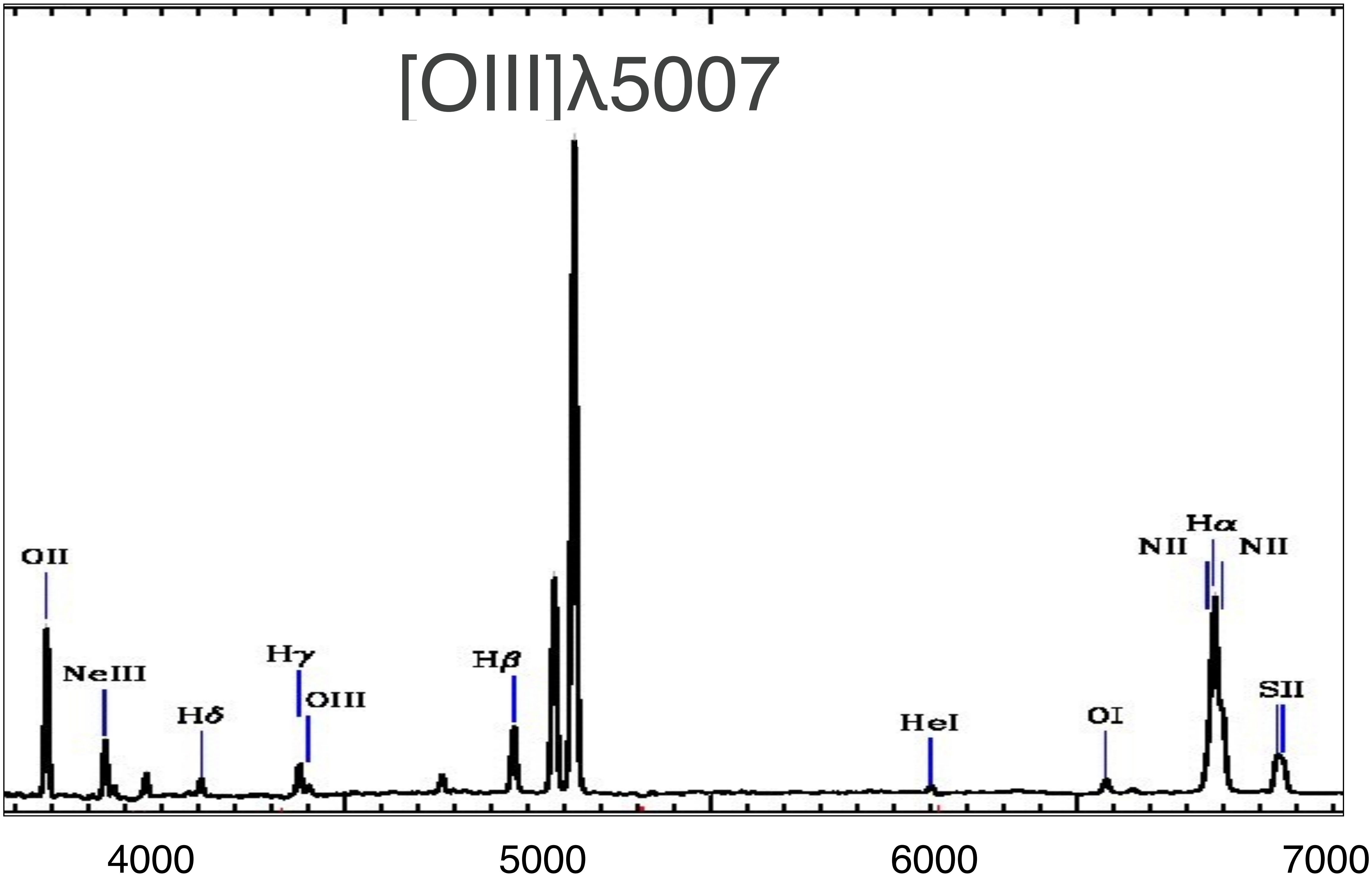




SDSS Spectrum

Obscured (Type-2) AGN





SDSS Spectrum

Part I: Multi-Phase Feedback Prototype

Molecular Outflows in J1356 with ALMA

Sun, Greene, Zakamska, & Nesvadba, ApJ (2014)

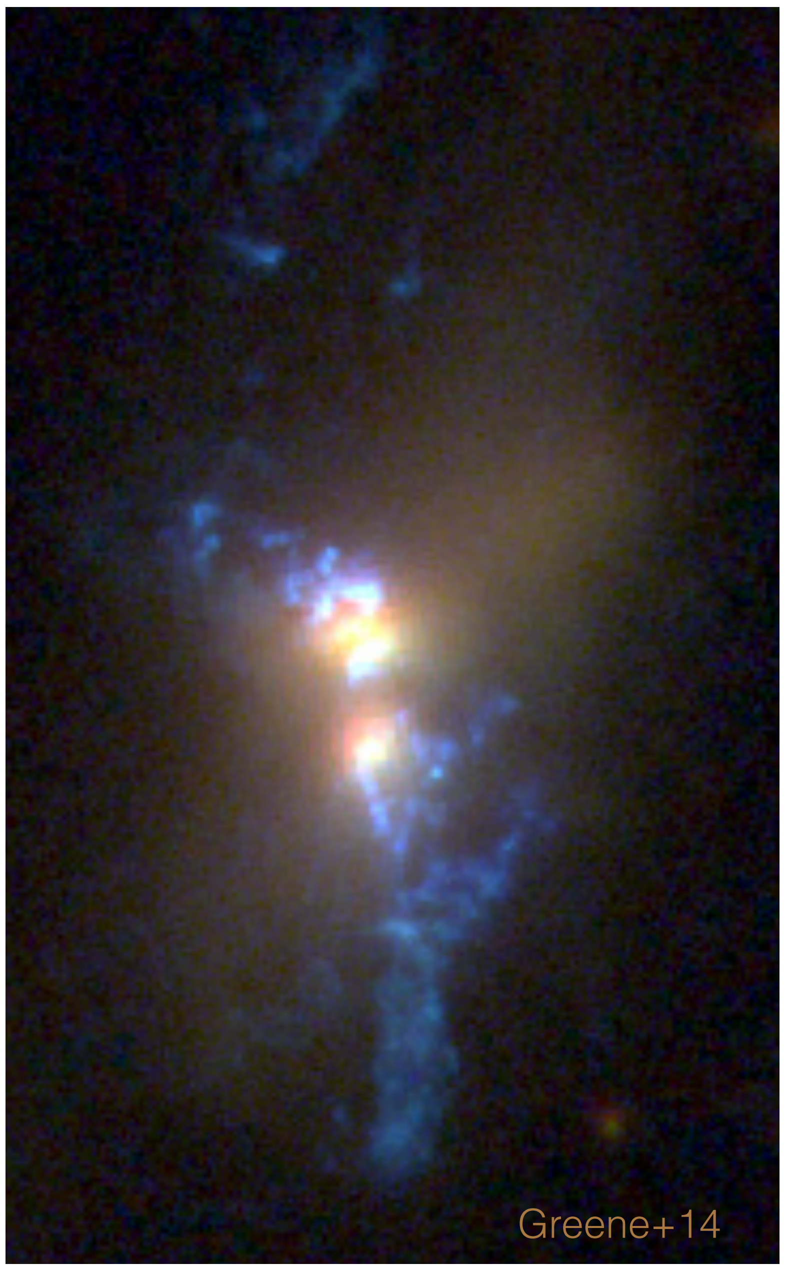
Part II: Is Outflow Common?

Part III: Explore a New Population

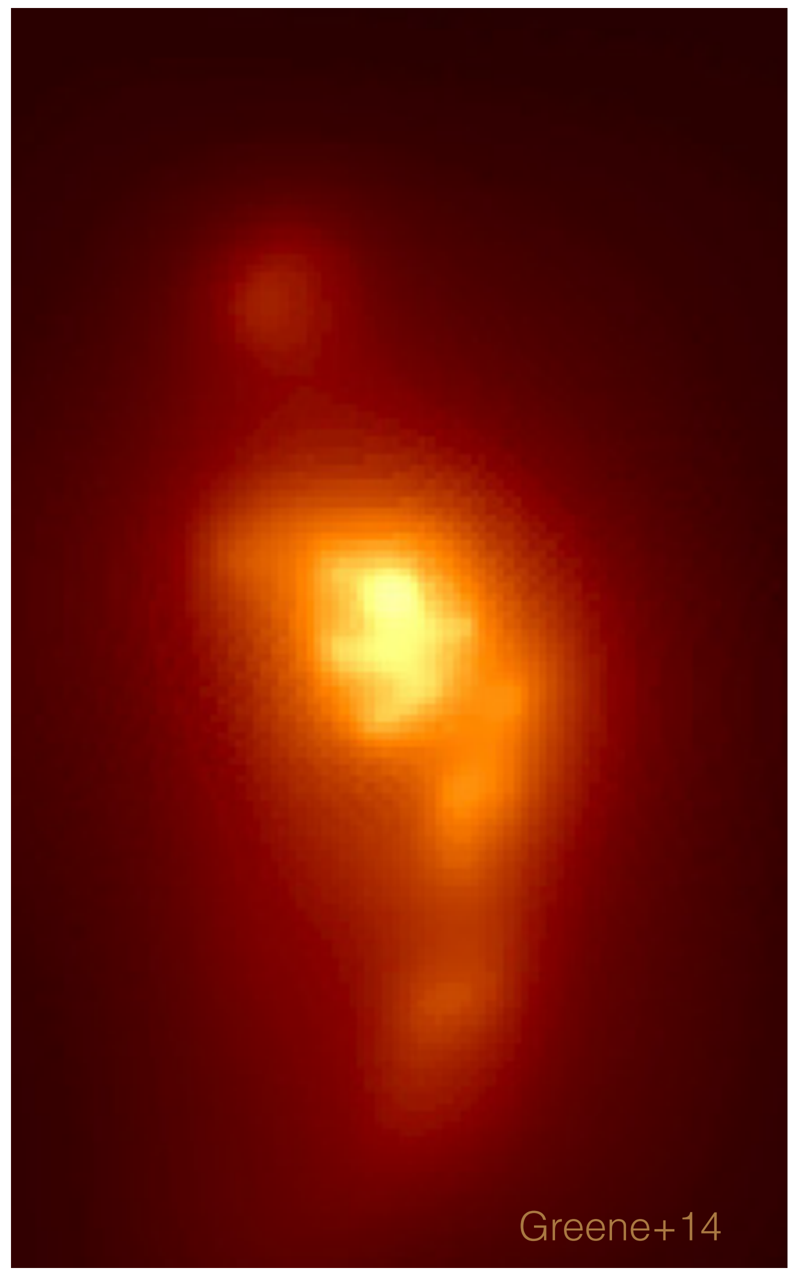
Multi-Phase Outflows in Obscured Quasar

SDSS J1356+1026, z=0.1, L_{bol}~10^{46} erg/s

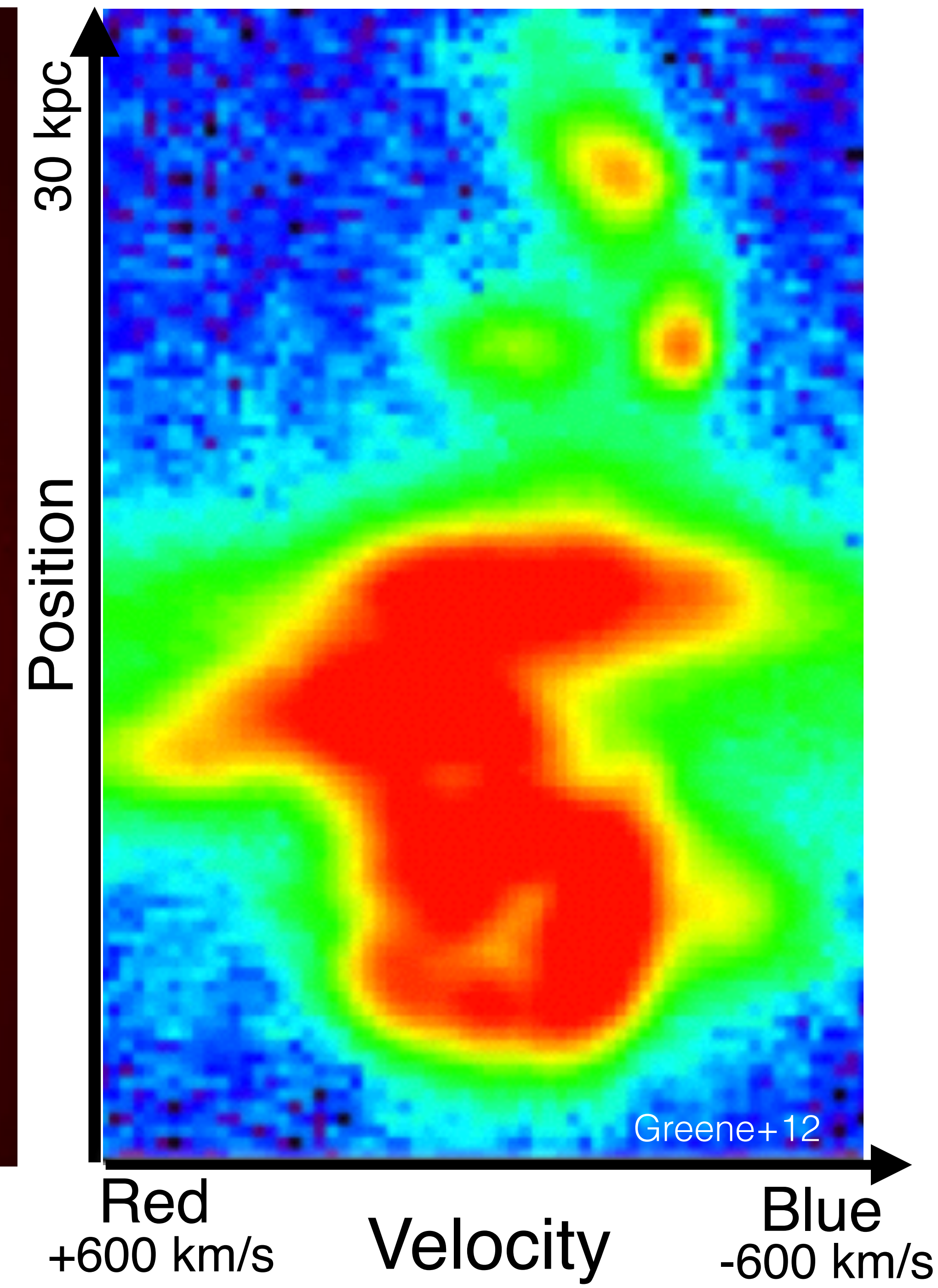
HST **Optical Image**



Chandra **Soft X-ray**



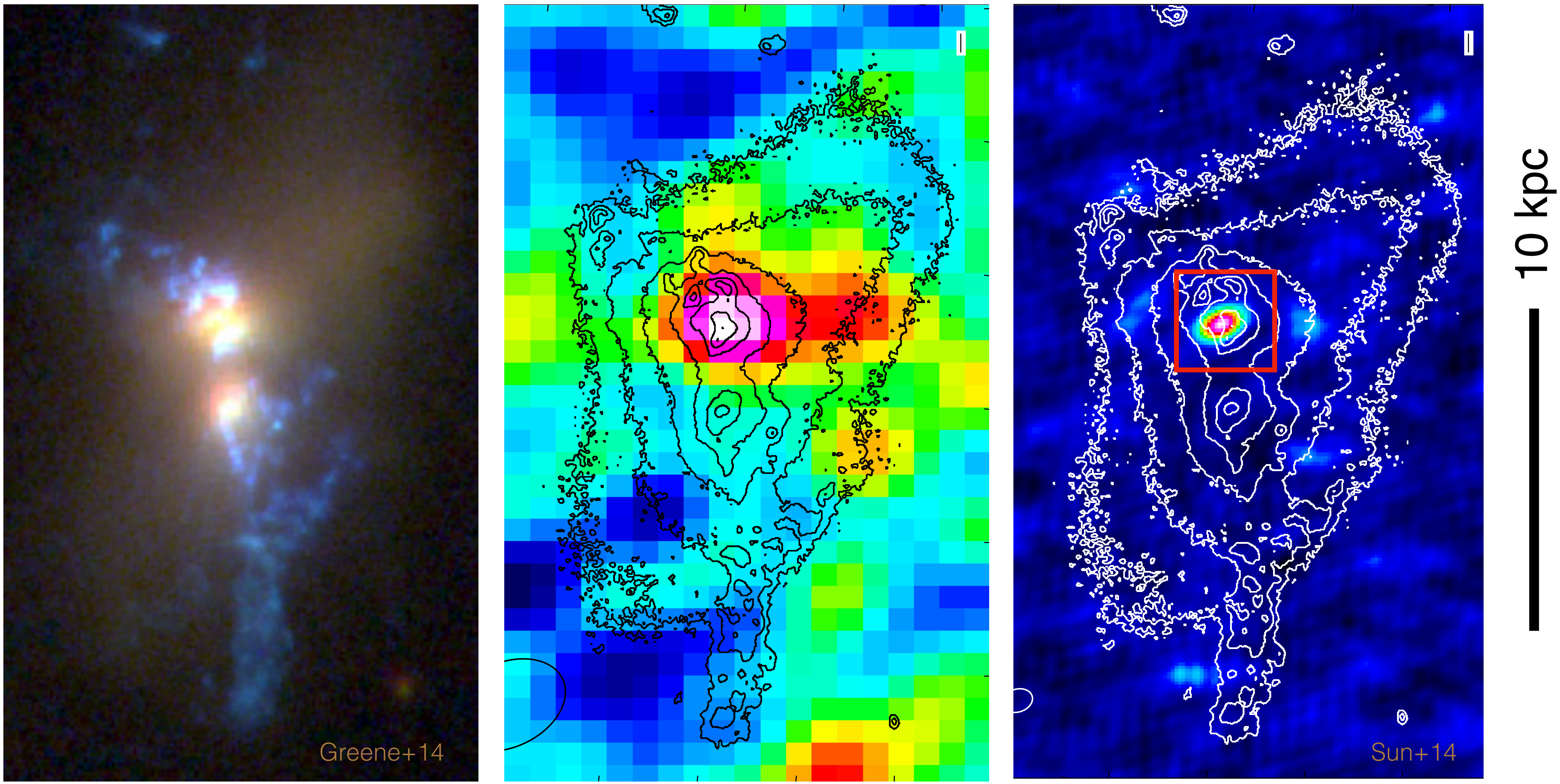
Magellan **[OIII] Spectrum**



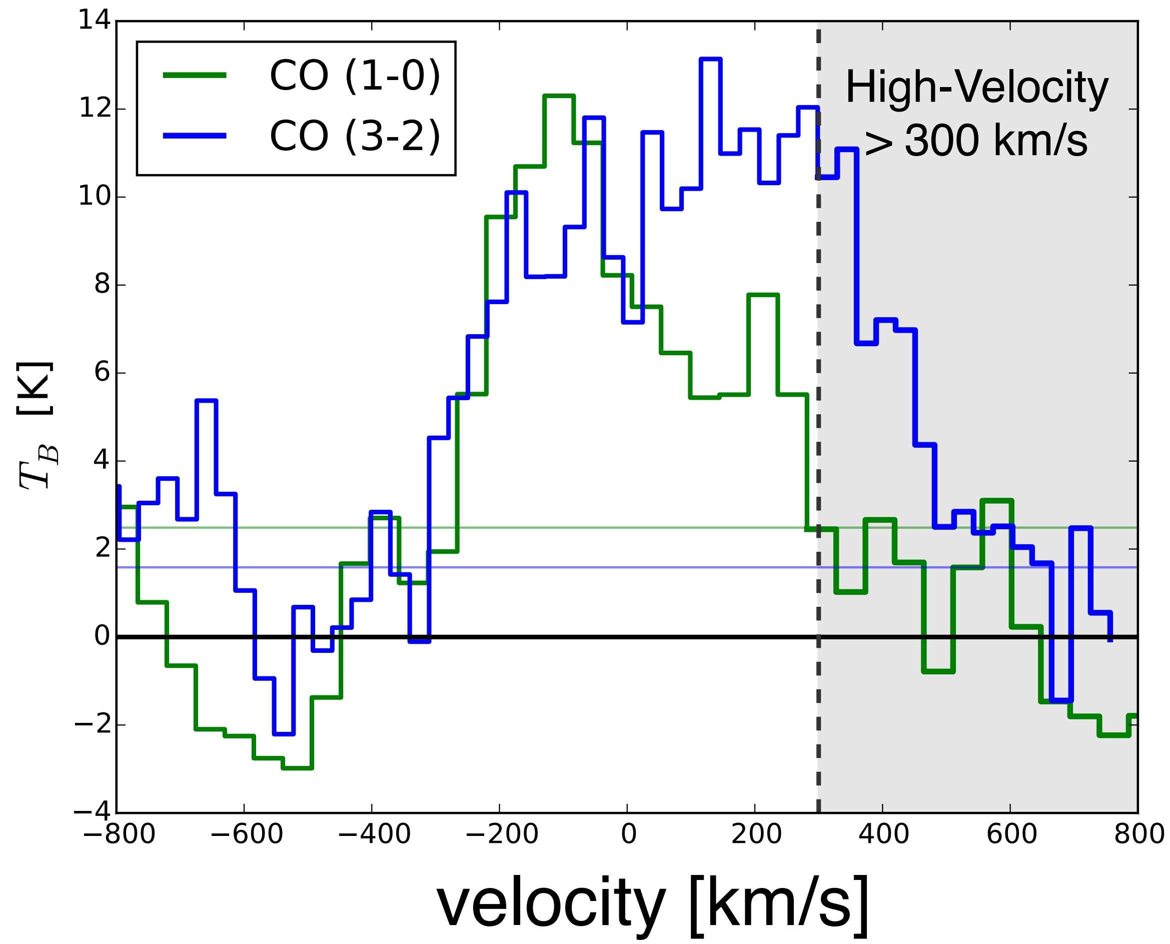
Molecular Gas with ALMA

ALMA cycle-0/cycle-1, resolution 1."9/0."35

HST **Optical Image** | ALMA **CO (1-0)** | ALMA **CO (3-2)**



CO Nuclear Spectrum



Outflow Properties

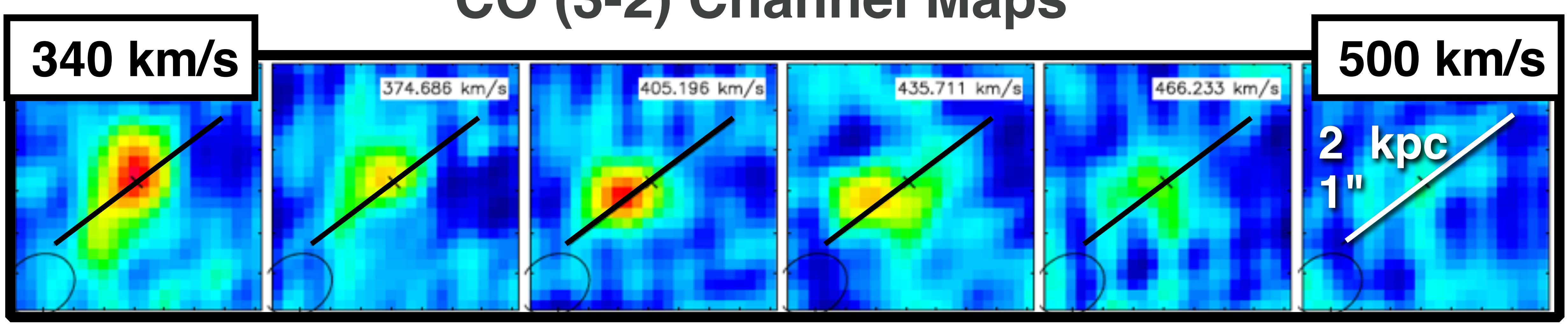
$r \approx 300$ pc

$v \approx 500$ km/s

$\dot{M} \approx 350\ M_\odot$/yr

$t_{dep} \approx 1$ Myr

CO (3-2) Channel Maps



Outflow is AGN Driven

$\dot{E}_{outflow} \sim 3\times10^{43}$ erg/s

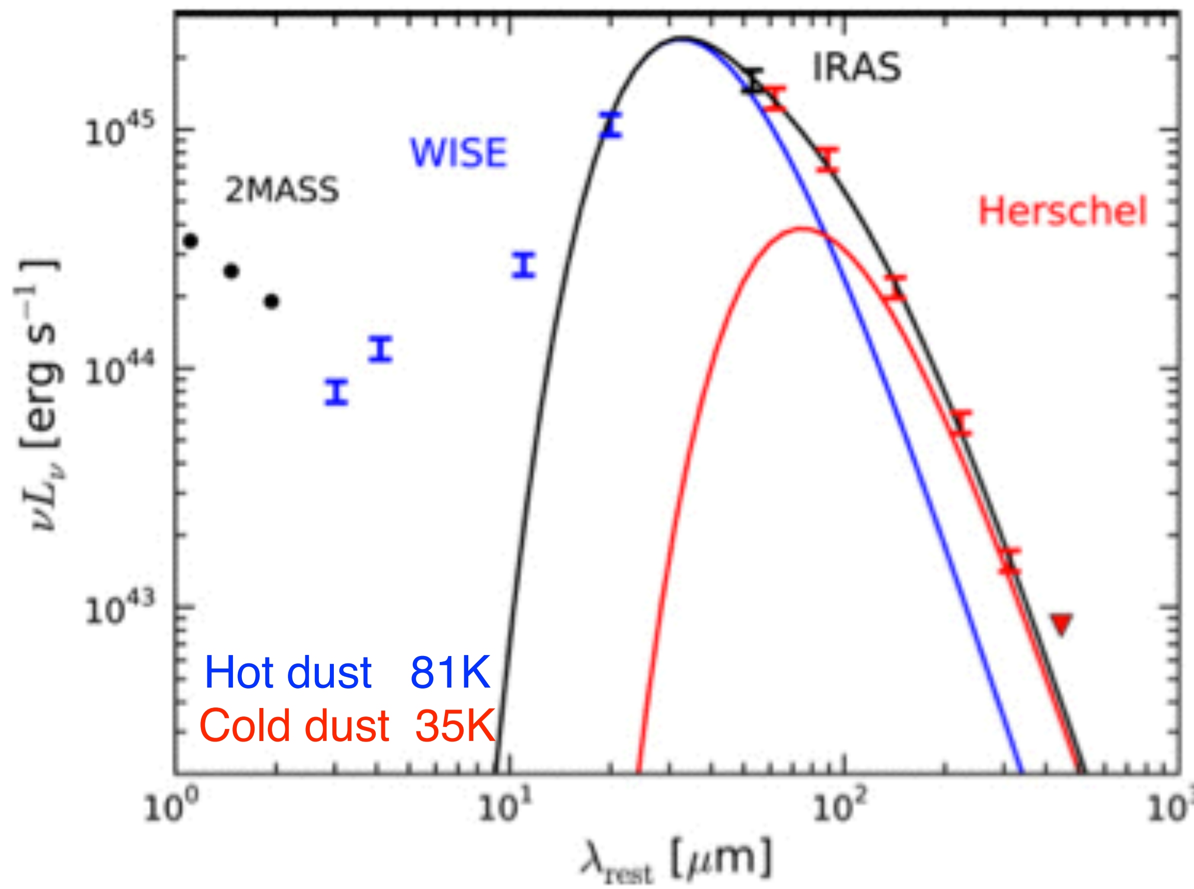
Constrains on star formation rate:

from FIR SED:

SFR < 21 $M_\odot$/yr (conservative)

from molecular (KS-law):

SFR ~ 1 $M_\odot$/yr



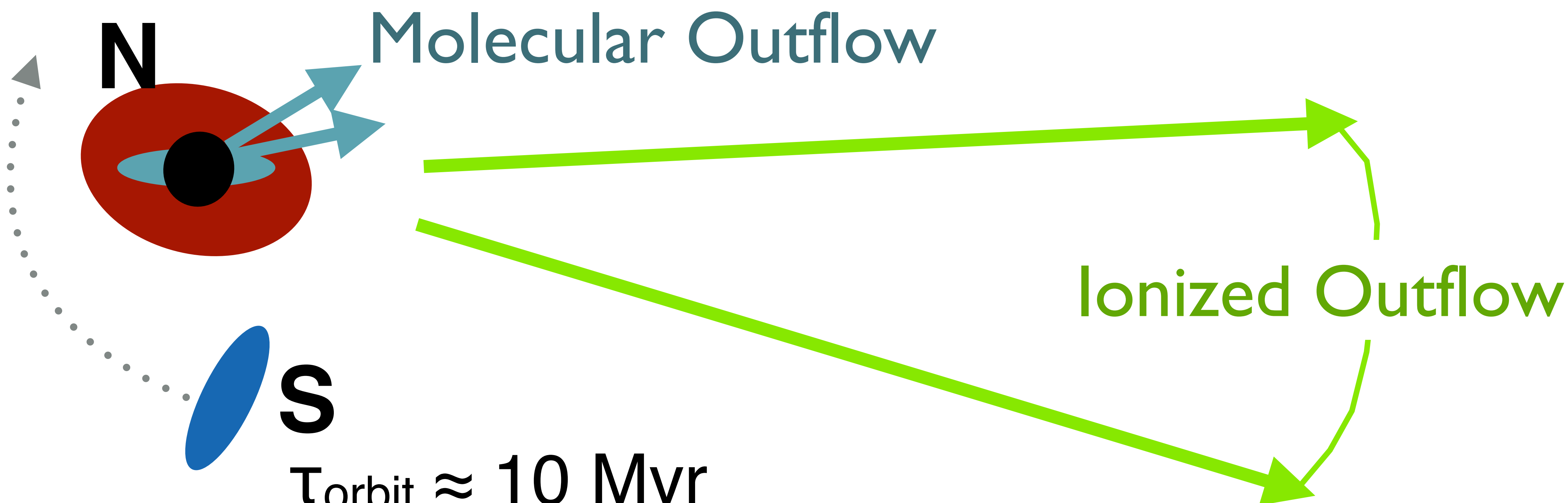
Star Formation Driven
If SFR = 21 $M_\odot$/yr
$\dot{E}_{Supernova} < \dot{E}_{outflow}$
(<1.5×10^{43} erg/s) (3×10^{43} erg/s)

OR

AGN Driven
$\dot{E}_{outflow} \approx 0.3\% \, L_{bol}$
$\dot{P}_{outflow} \approx 3 \, L_{bol}/c$

Episodic AGN Feedback

Compact Molecular Outflow	Extended Ionized Outflow
$r \approx 300$ pc	$r \approx 10$ kpc
$t_{dyn} \approx 0.6$ Myr	$t_{dyn} \approx 10$ Myr
$M \approx 7\times10^{7}\ M_{\odot}$	$M \gtrsim 5\times10^{7}\ M_{\odot}$



$\tau_{orbit} \approx 10$ Myr

Part I Summary:

- SDSS J1356+1026 is likely **elliptical/disk merger** triggering AGN feedback and multi-phase outflows

- The **molecular outflow could deplete** the molecular reservoir in **~ Myr**.

- The molecular and ionized outflows are likely distinct events driven by **AGN variability on a time scale of 10 Myr.**

Future of ALMA

Capacity	Cycle-0/1	Full Capacity
Antennae (12-m)	27	66
Resolution [CO(3-2)]	0.35″	0.035″

Accepted ALMA Cyc-3 Proposal for J1356 **-** Sun, Greene, and Zakamska

Higher resolution CO (3-2) to resolve outflow structure

HCN to investigate the dense gas and acceleration mechanism

Part I: Multi-phase feedback prototype

Part II: Is outflow common?

Ionized Outflows in Luminous Quasars

Sun et al. in prep

Part III: Explore a new population

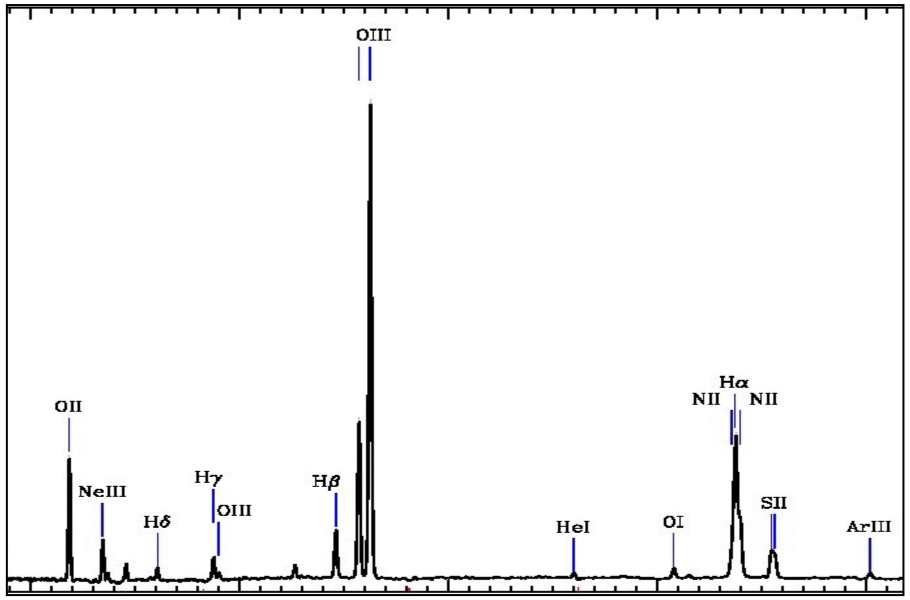
Select Nearby Luminous Quasar

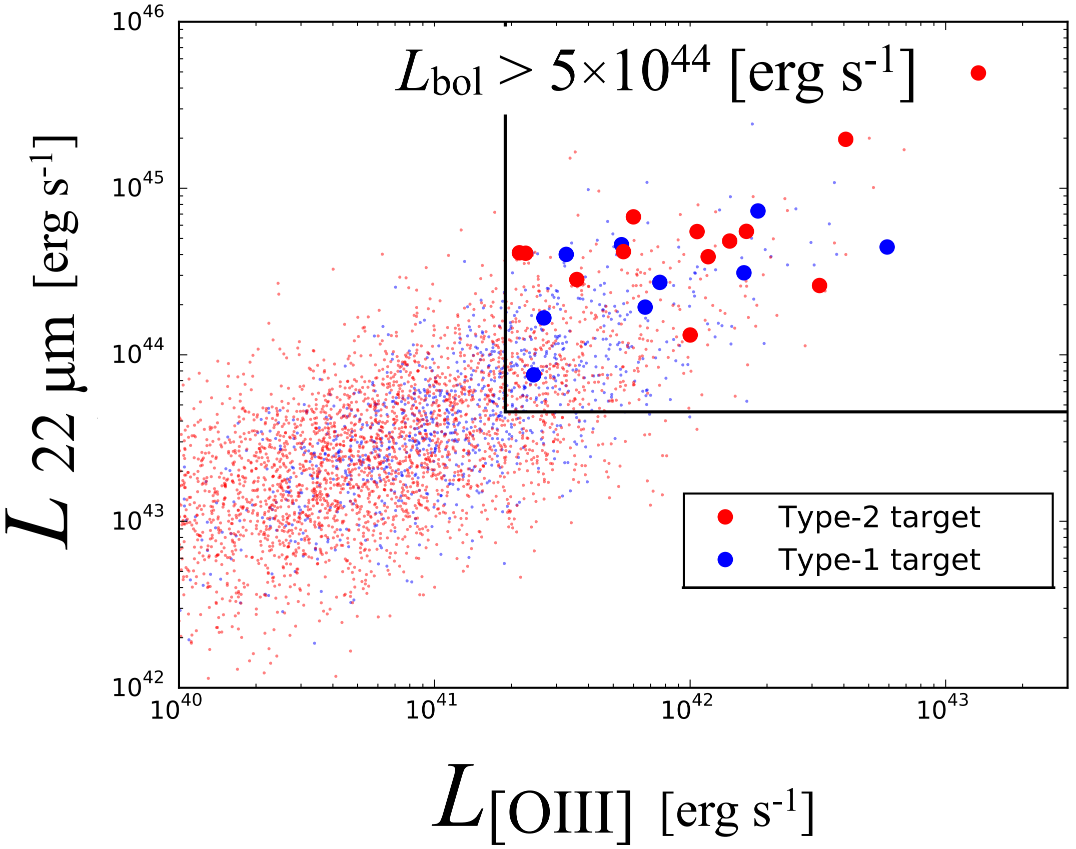
1. SDSS spectroscopically identified
   Mullaney+13

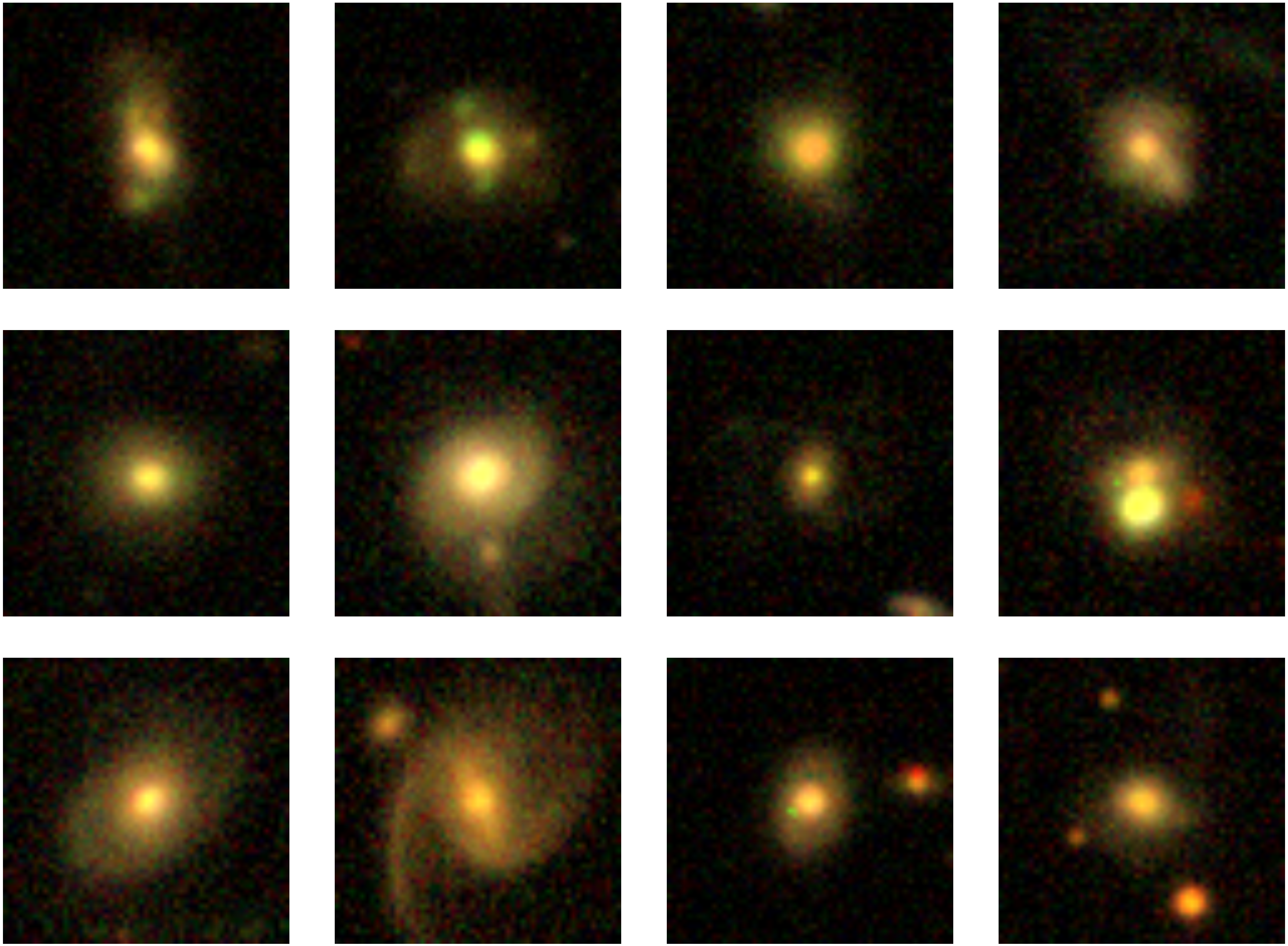
2. Nearby z < 0.2

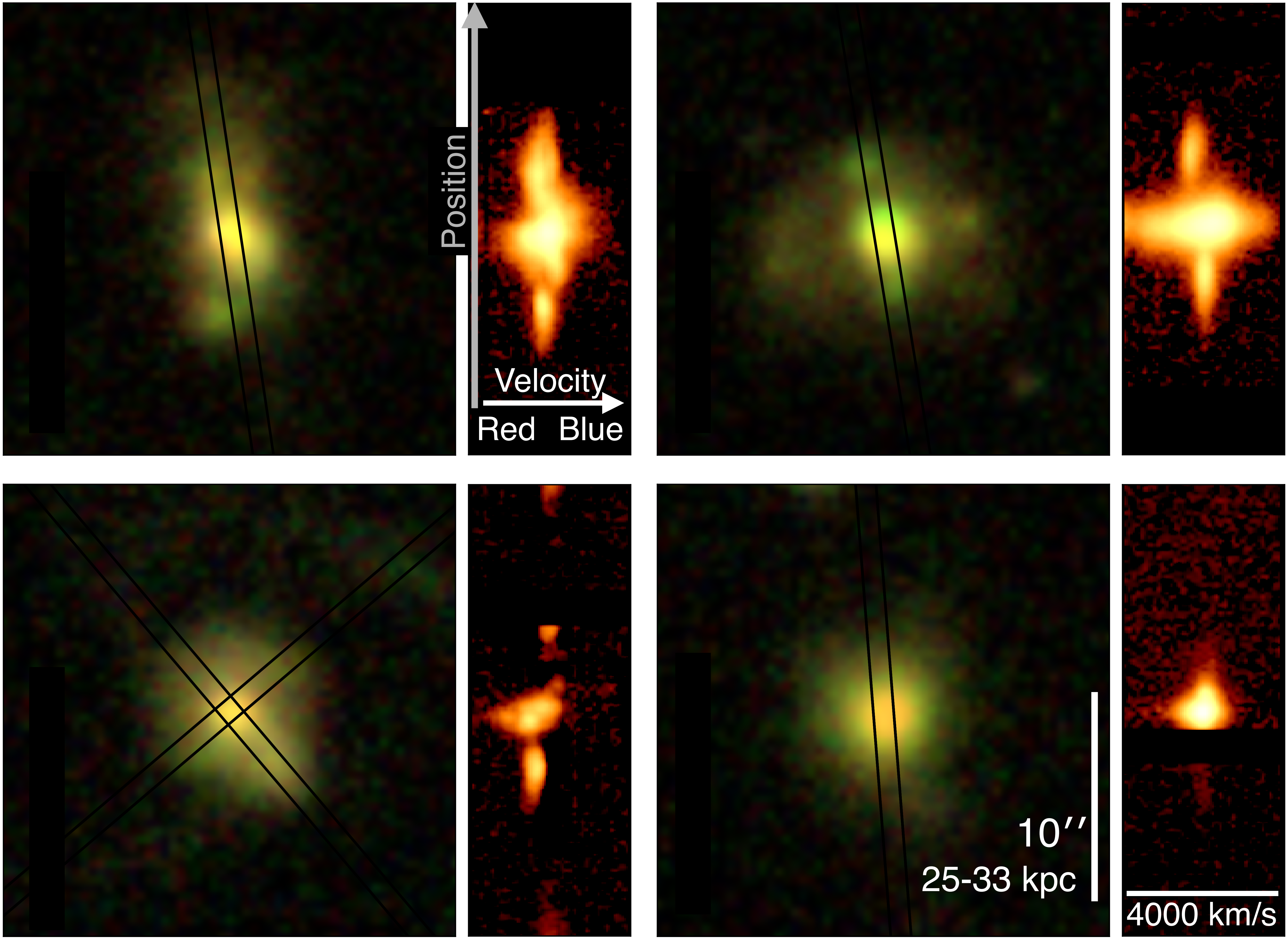
3. Luminous $L_{bol} > 5\times10^{44}$ erg/s
   from [OIII] and WISE 22 µm Luminosities

4. 13 Obscured (Type-2)
   9 Unobscured (Type-1)

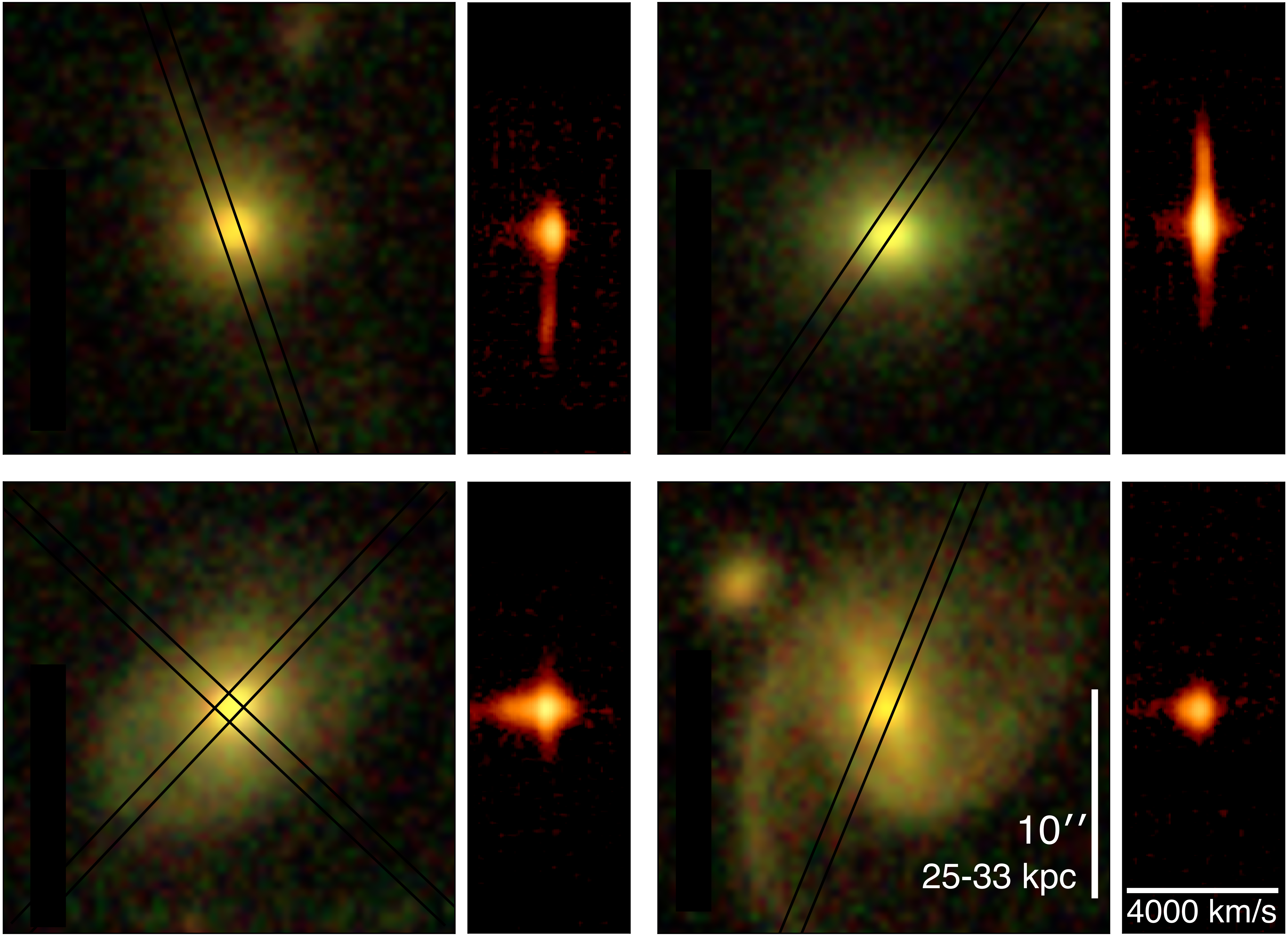




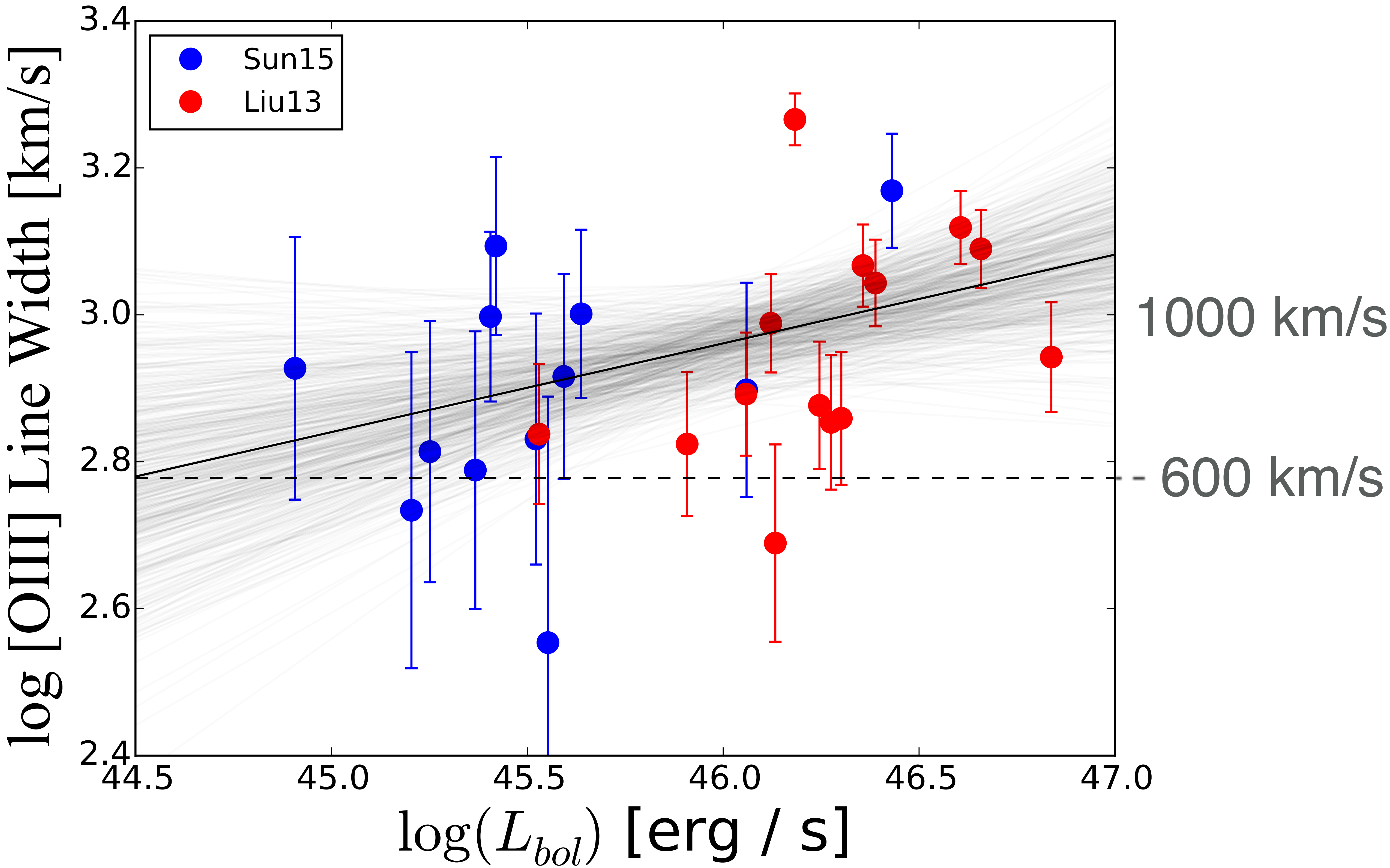




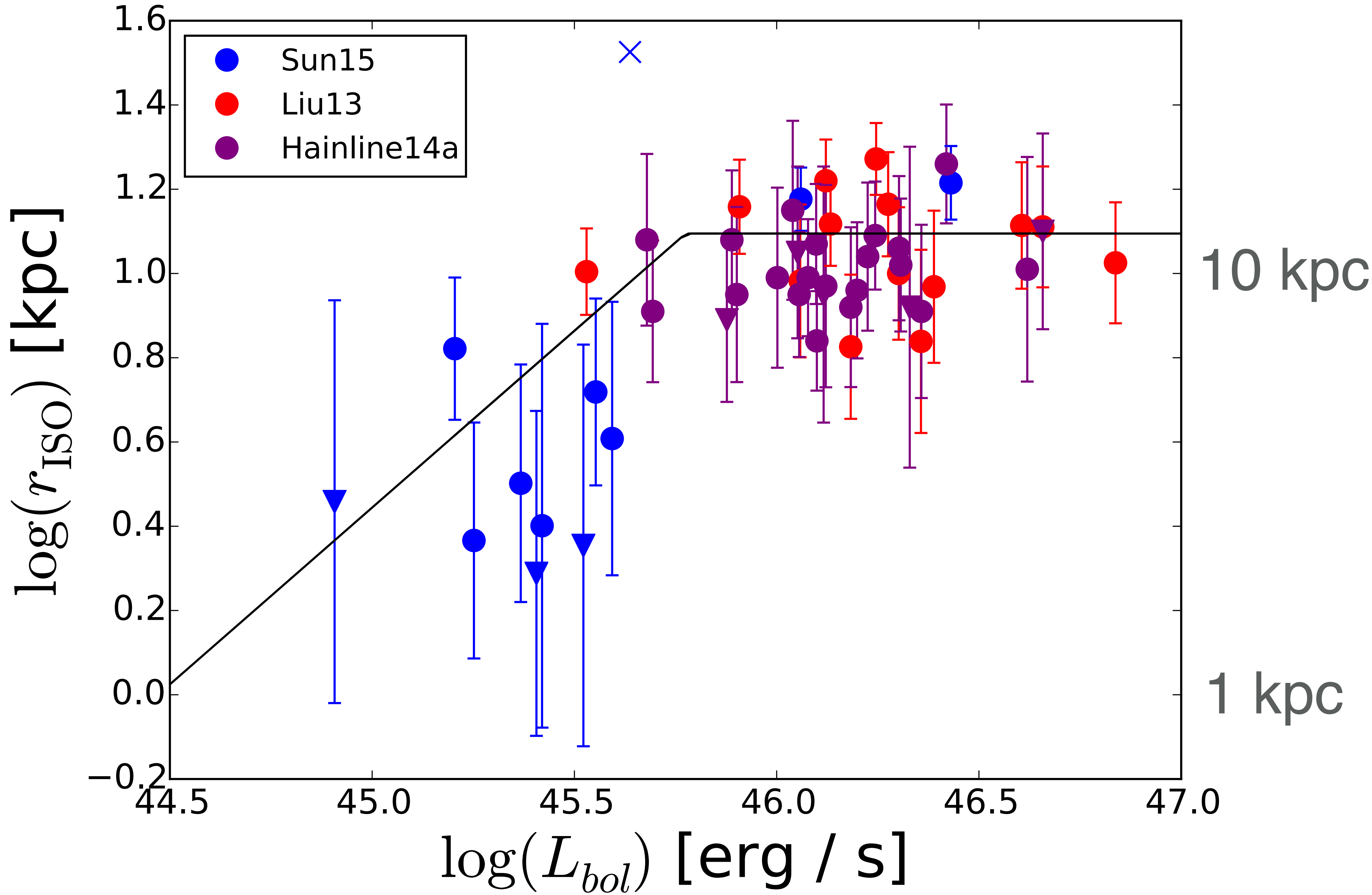
Position
Velocity
Red
Blue
10′′
25-33 kpc
4000 km/s


10′′
25-33 kpc
4000 km/s

High Velocity Outflows?

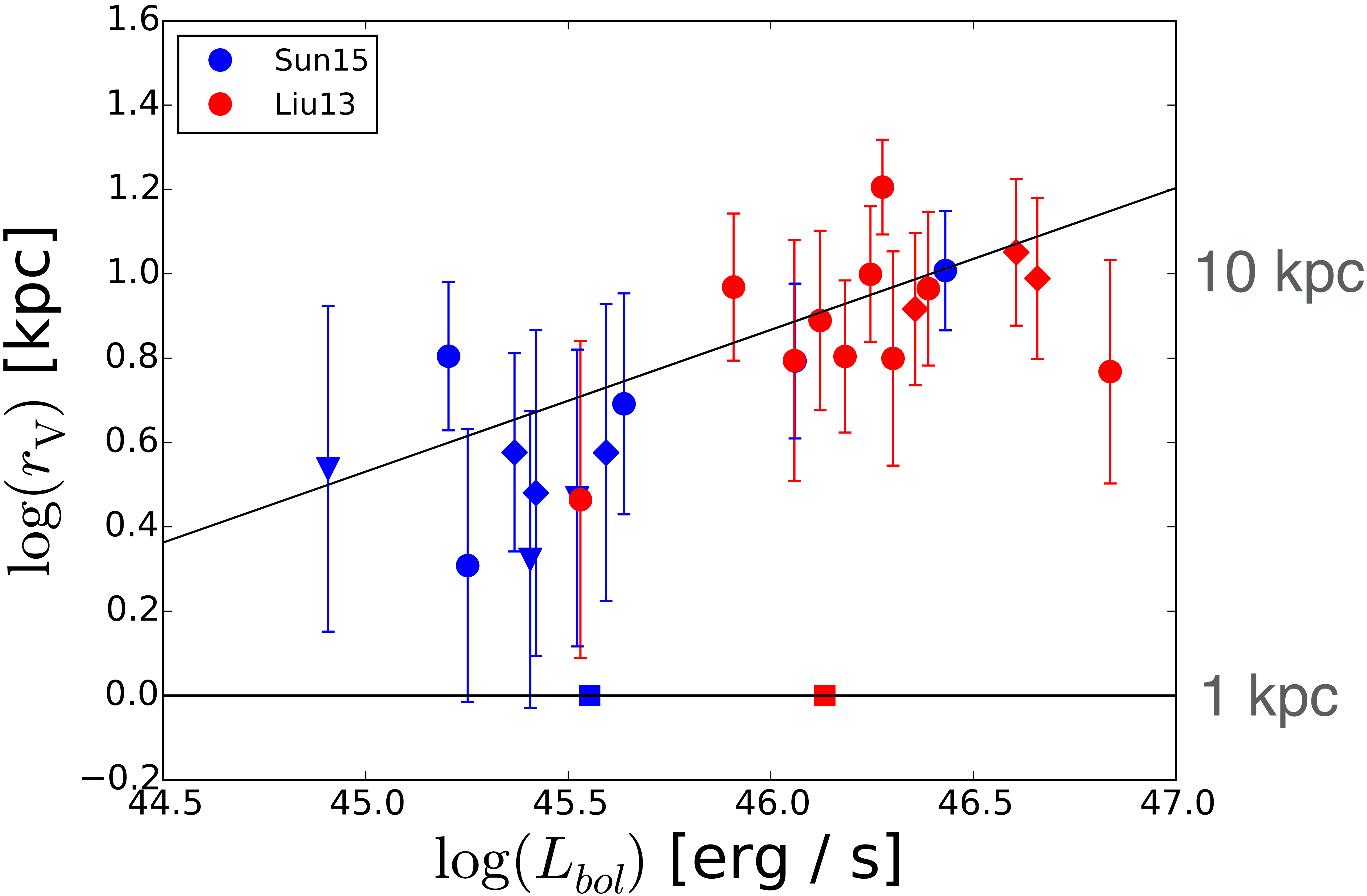


Outflows Sizes r_{iso} - isophoto size of [OIII] emitting region

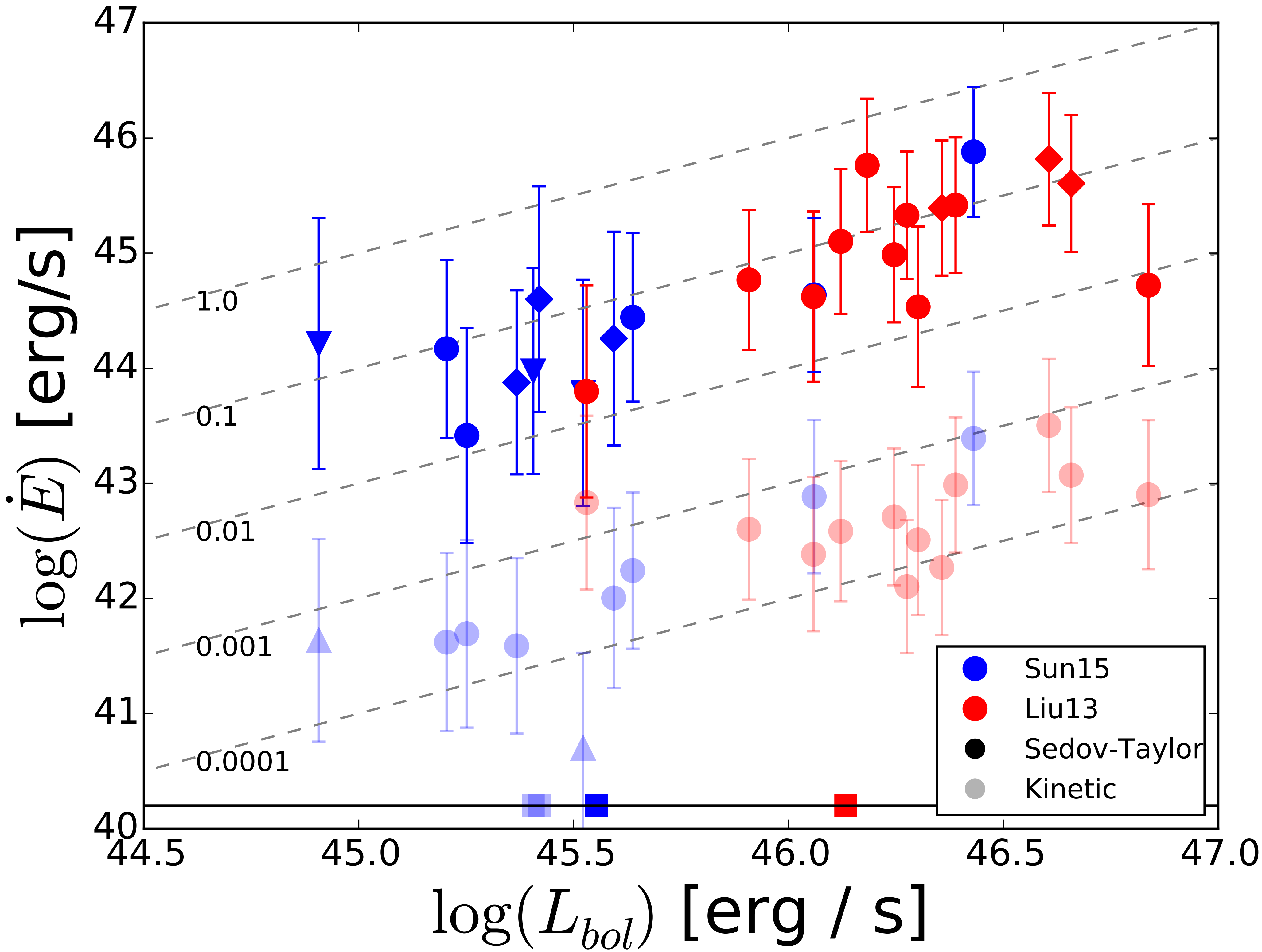


Outflows Sizes

r_V - size of high velocity gas



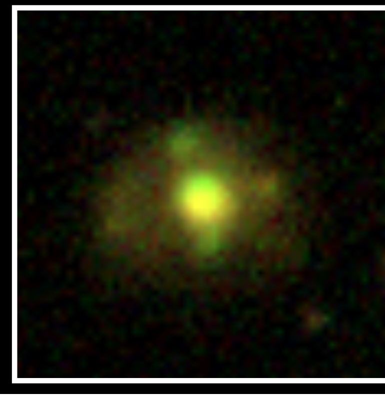
Energy Efficiency



Part II Summary:

- Discovered two > 10 kpc extended outflows
- Beyond $L_{bol} \sim 10^{45}$ erg/s, most AGN drive ionized outflows
- Outflow size and energy depends smoothly on L_{bol}. No sign for an L_{bol} threshold for outflow.
- Feedback energy efficiency can be a constant.

Multi-Wavelength Follow-ups



SMA 2014B Accepted - 2 tracks — Sun and Greene

Detect CO (3-2) to search for molecular outflows

Chandra Cyc-17 Accepted - 27+39 ks — Pardo, Goulding, Greene, and Sun

Spatially resolve the X-ray emitting hot wind

Part I: Multi-phase feedback prototype

Part II: Is outflow common?

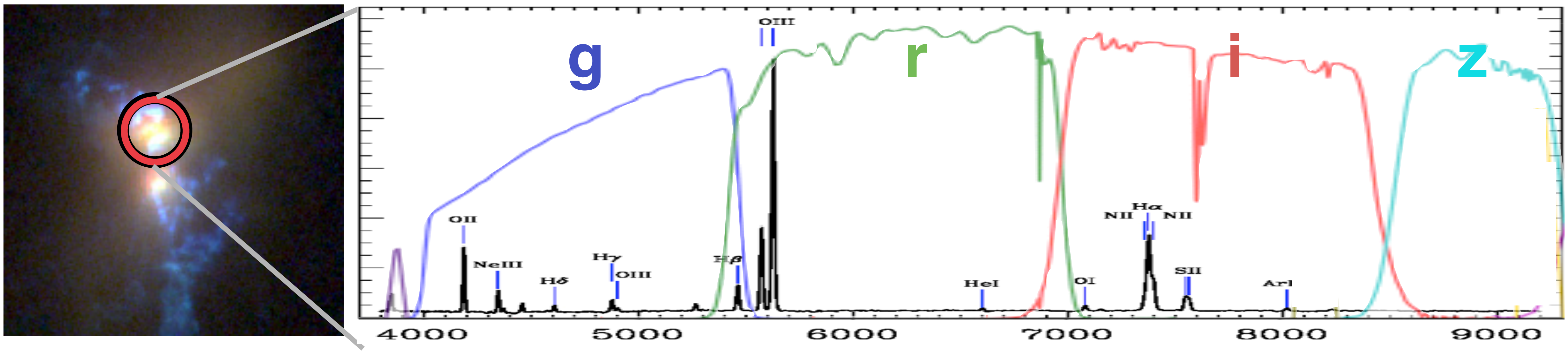
Part III: Explore a new population

Imaging Selection of Extended Outflows

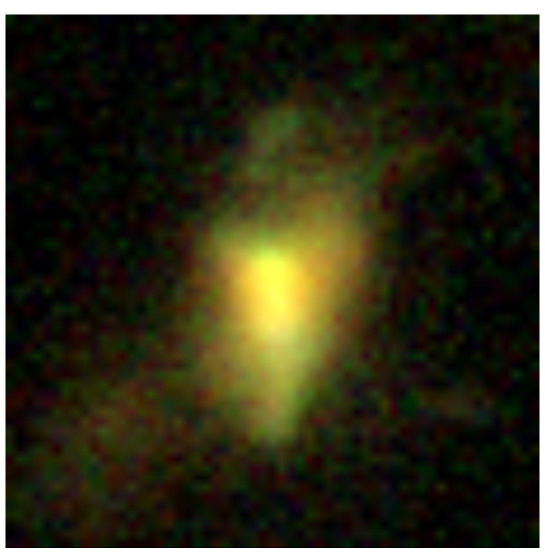
work in progress…

Broadband Selection for Extended Outflows

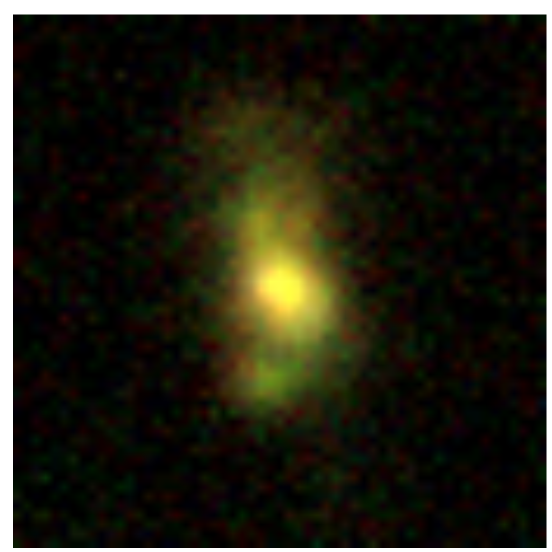
SDSS Fiber Spectra



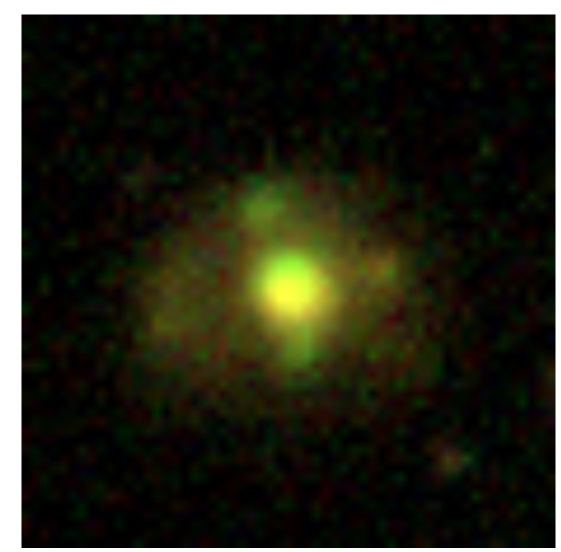
SDSS J1356+1026 z=0.1



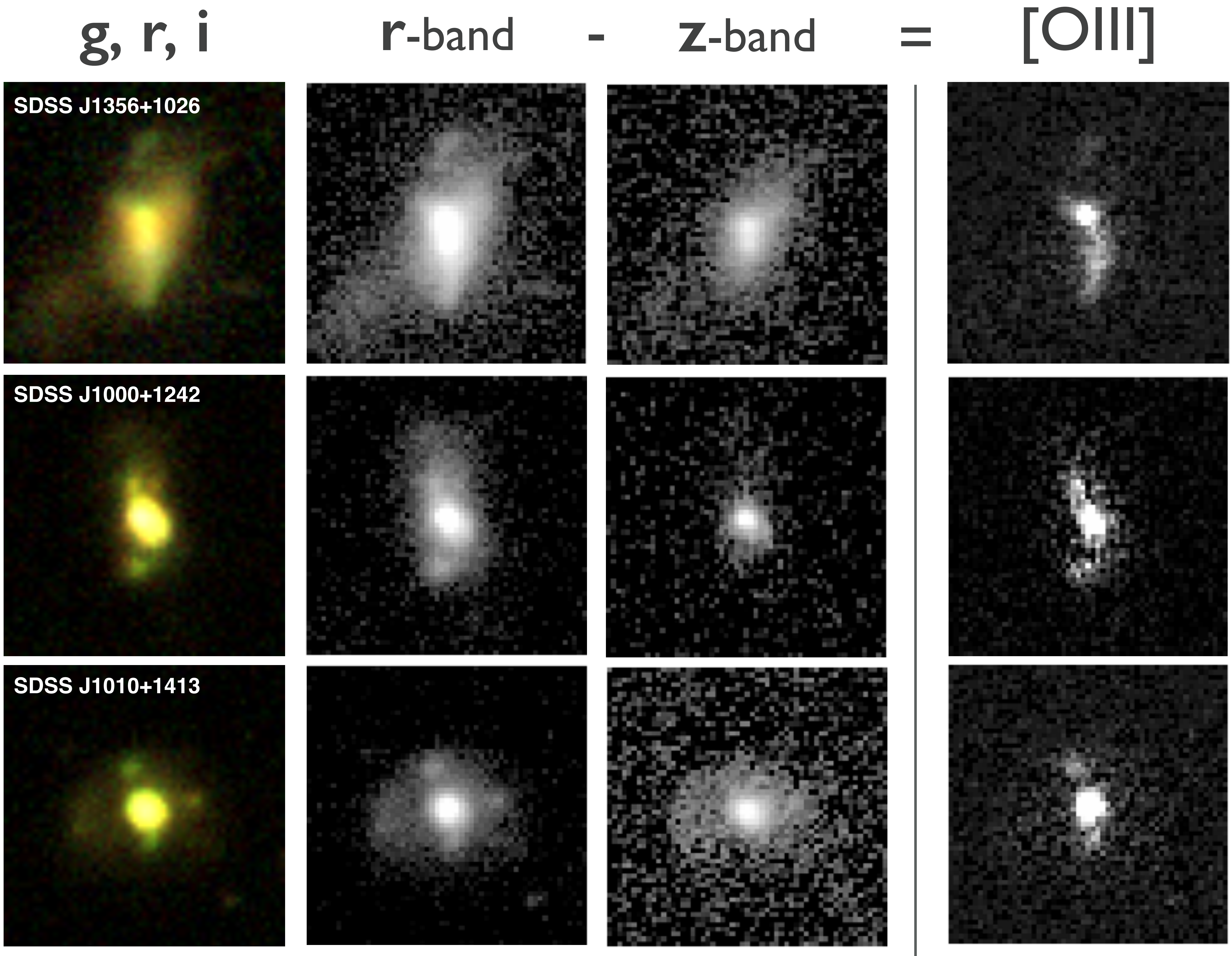
SDSS J1000+1242 z=0.15



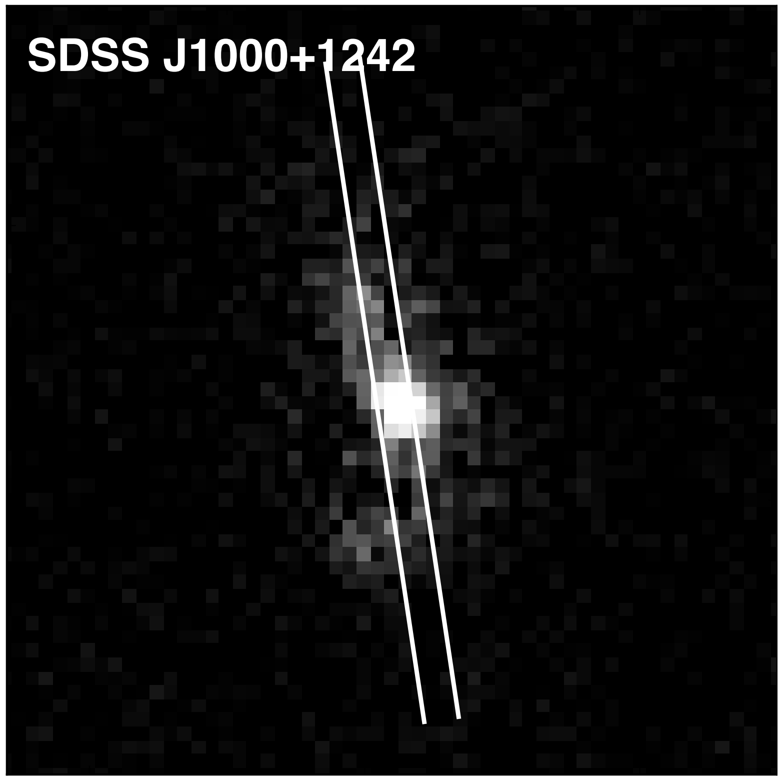
SDSS J1010+1413 z=0.20

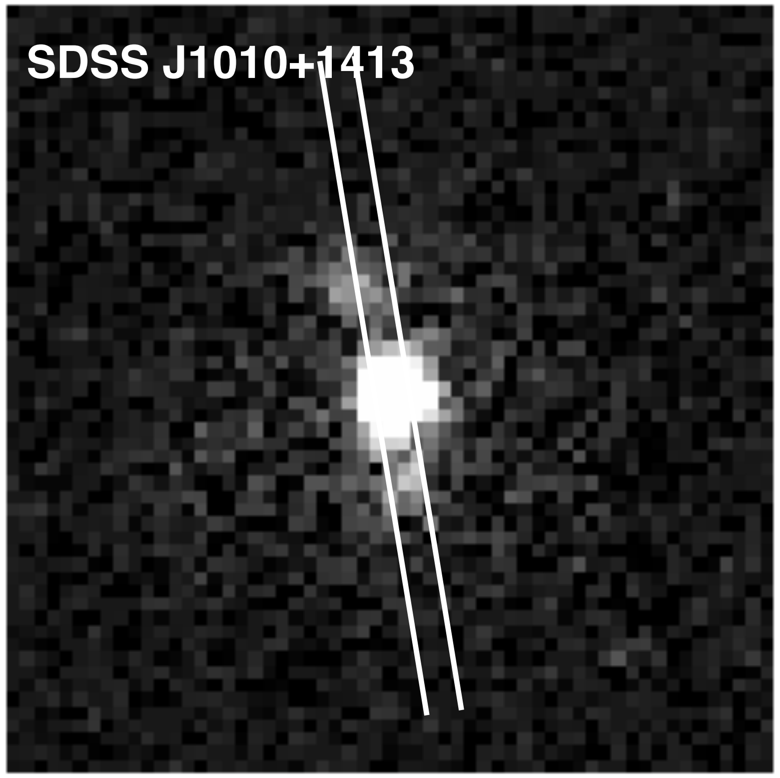


20”×20”

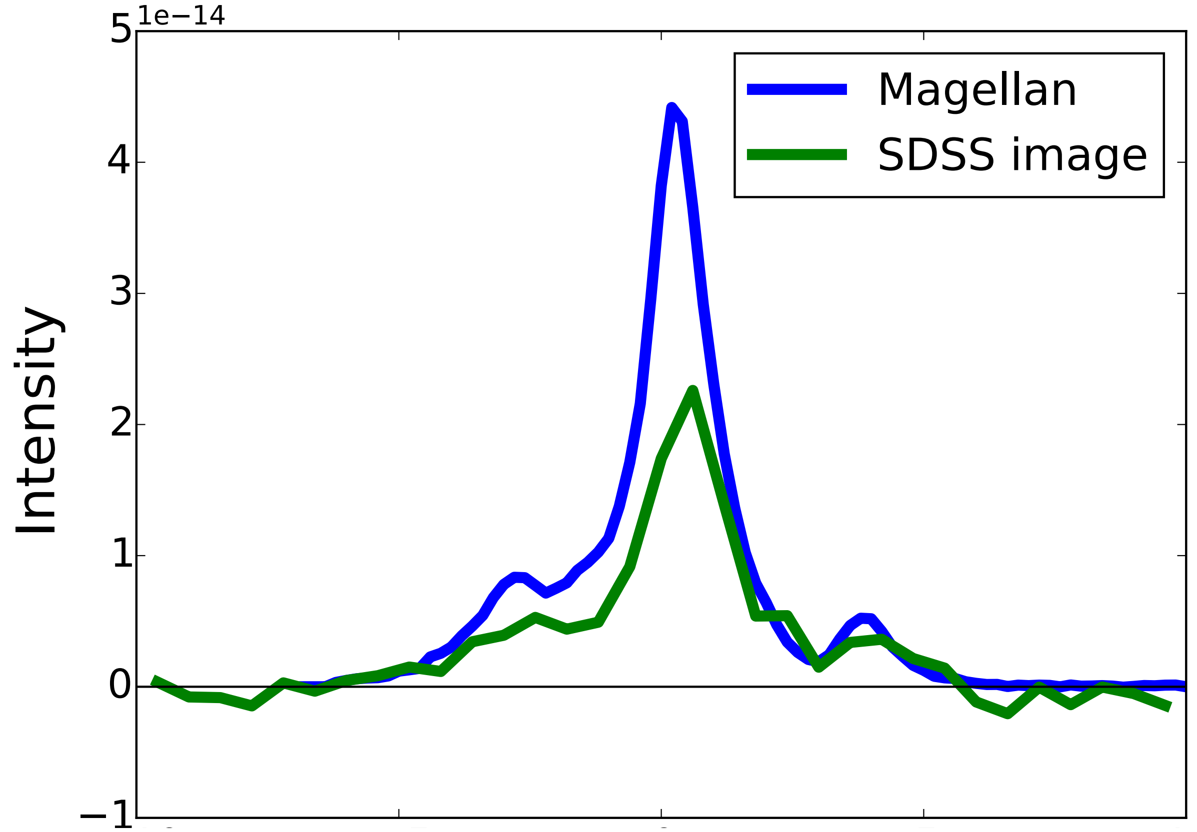

g, r, i
r-band
-
z-band
=
[OIII]
SDSS J1356+1026
SDSS J1000+1242
SDSS J1010+1413

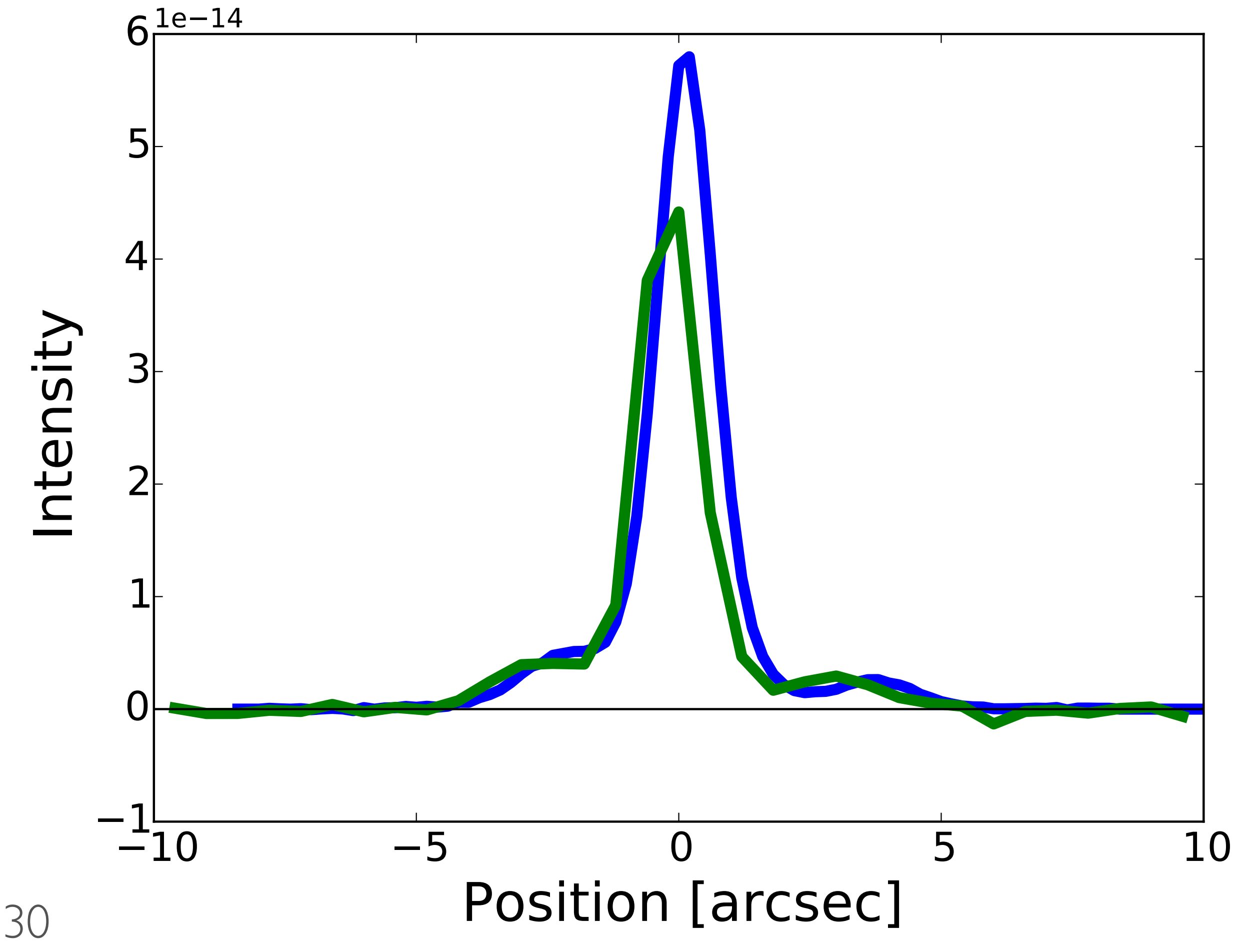
SDSS Images



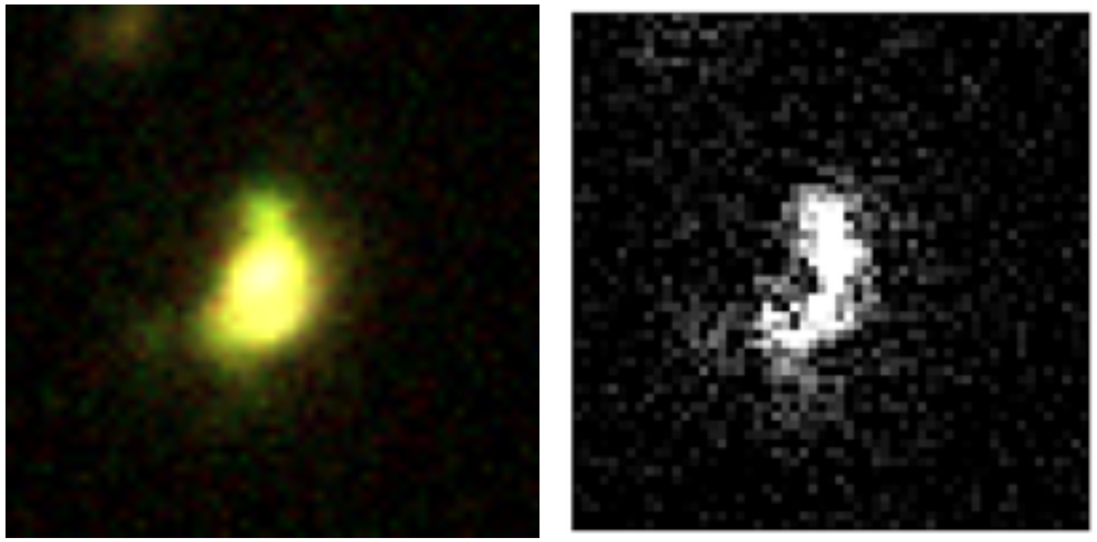


Magellan Spectrum



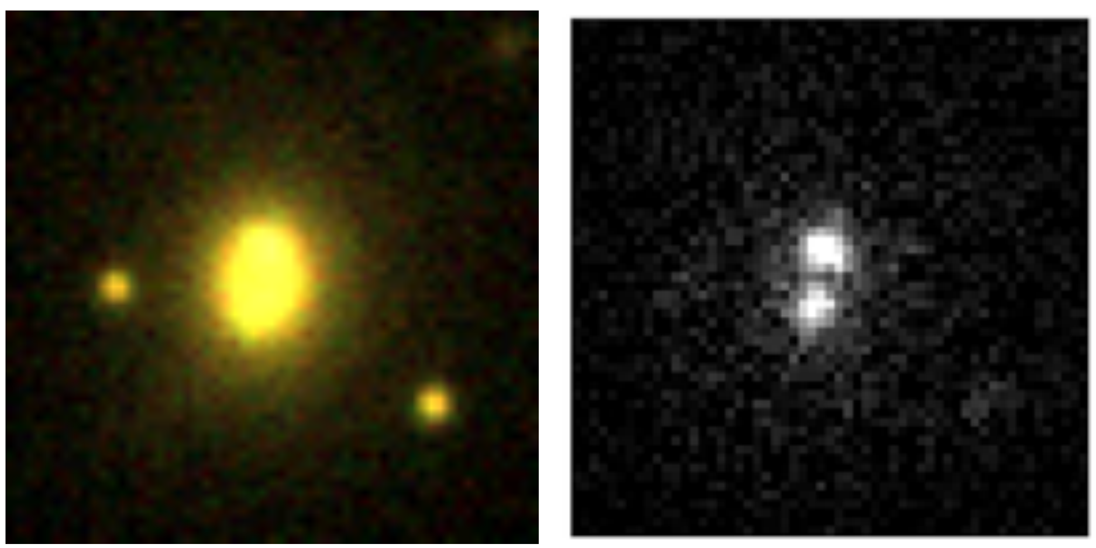


Interesting Objects from SDSS



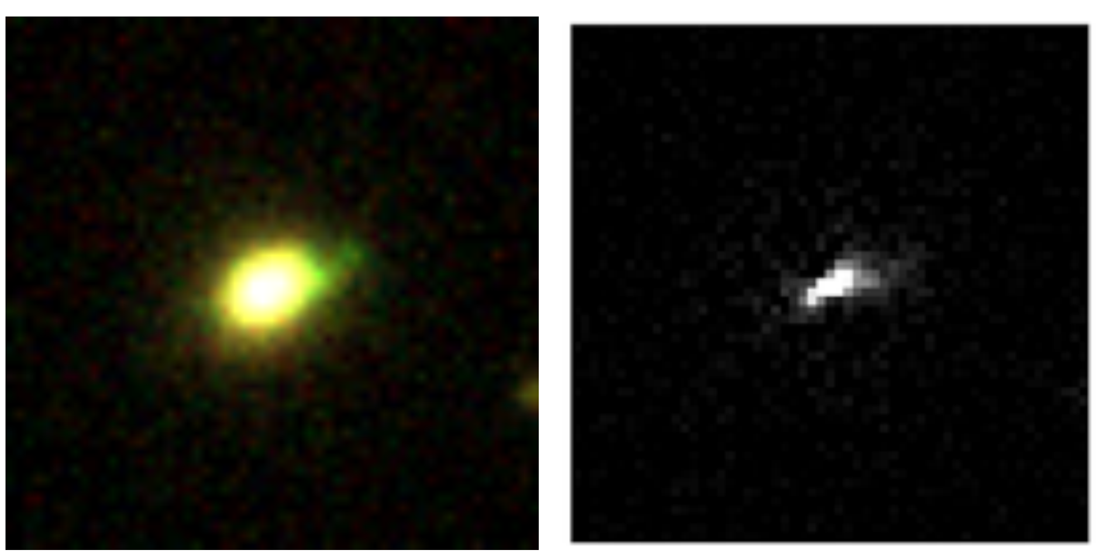
Supperbubble?

- z=0.20, Lbol ~ $8*10^{45}$
- [OIII] size 8.5” ~ 28 kpc



Dual AGN?

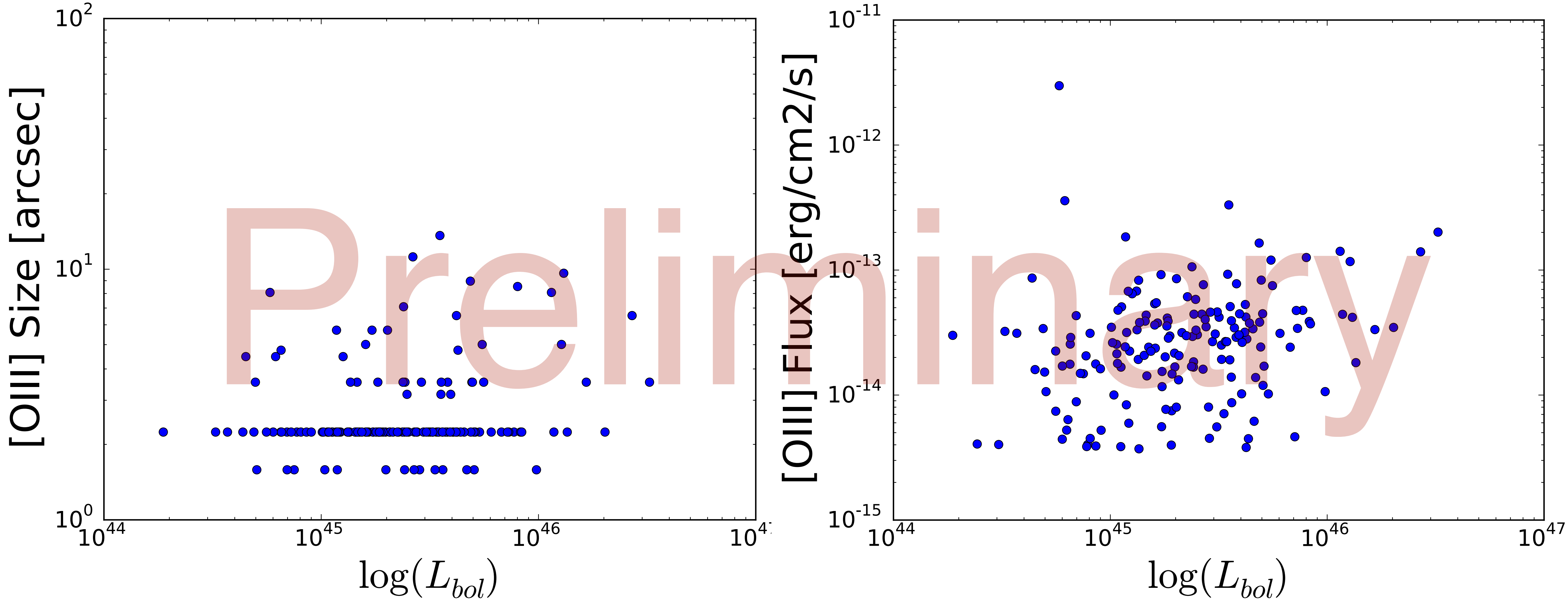
- z=0.1, Lbol ~ $1*10^{45}$
- [OIII] size ~ 5.7” ~ 13 kpc



AGN Ionization Cone?

- z=0.15, Lbol ~ $5*10^{45}$
- [OIII] size ~ 5.0” ~ 13 kpc

Constraining [OIII] Size Distribution from SDSS



Part III Summary:

Broadband imaging subtraction can:

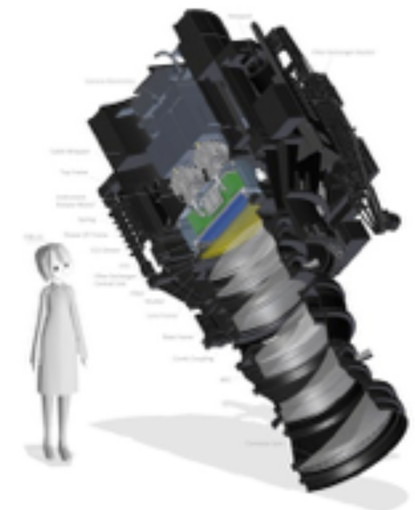
- constrain [OIII] nebula morphologies
- select extended [OIII] nebula - outflow candidates
- measures R_{iso} distributions

Next Steps:

- Understand contaminations
- Predicting R_V from imaging Riso, SDSS spectrum [OIII] line width, and WISE

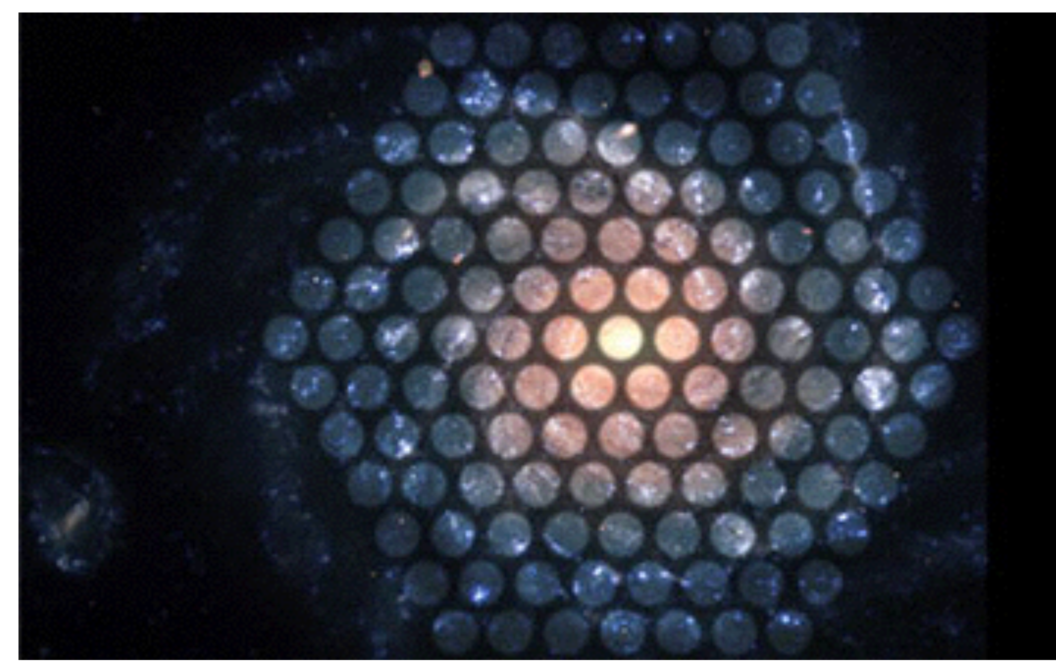
Subaru Hyper Suprime-Cam

- 8.2 m telescope × 2 deg^2 FoV
- Area: 1400 deg^2 (wide-layer)
- Depth: 26 mag
  (4-mag deeper than SDSS)
- Hundreds of extended nebula



SDSS-IV MaNGA

- IFU spectroscopy survey



Large Synoptic Survey Telescope

Capacity	SDSS	HSC	LSST
Depth (*r*-mag)	23	26	27.7
Area [deg^2]	15,000	1,400	20,000

- 10 years survey with six bands u, g, r, i z, y
- 6.7 m telescope × 9.6 deg^2 FoV

Take home messages:

- AGN outflows are **multi-scaled** and **multi-phased**, and can deplete star formation fuel in the galaxy.
- **Most AGN beyond 10^{45} erg/s drive ionized outflows**
- Broadband imaging surveys open a new window for feedback studies

Future Directions

Imaging Survey

Spectroscopy Survey

Multi-Wavelength
Follow-up

Thank you